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Optimal Sizing and Placement of Distributed Generators in Unbalanced Distribution Networks: An Analytical Perspective

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Abstract: In modern power systems, integrating distributed generation (DG) is essential to meet growing energy demands while optimizing operational and financial efficiency. However, arbitrary placement of DG units can significantly impact on power losses and voltage profiles of the network, depending on their capacity and location. Precise optimization of both the location and capacity of DG units is therefore crucial to maximizing their benefits and mitigating over-voltage issues. This paper presents an analytical approach that employs an Exact Loss Formula to determine the optimal capacity and location for DGs, specifically within unbalanced practical distribution networks, which remains an area not thoroughly addressed in previous literature. The proposed method is validated on the standard IEEE 33-bus network and further applied to a real-world distribution network in Kurunegala District, Sri Lanka, with rooftop solar as the DG. Test results demonstrate the effectiveness of the proposed method in minimizing power losses and addressing voltage-related challenges in unbalanced distribution systems.

Keywords: Power Loss Minimization, Rooftop Solar PV, Voltage Unbalance, Over Voltage

1. Introduction

The global demand for electrical energy is rapidly increasing due to technological advancements, improvement of living standards, and population growth. This continuous rise in demand has led to energy crises in several countries, caused by a mismatch between generation and demand, compounded by system losses [1]. Since adding more power plants to the system requires significant capital investment, the focus has been shifted toward enhancing the efficiency of power systems [2]. One effective approach to achieving this is by minimizing losses within electrical systems [3].

At the same time, technological advancements are driving significant transformations in traditional power systems. One of the major changes is the integration of renewable-based small-scale and medium-scale power generating plants (e.g., solar, wind, etc.) at low and medium voltage levels. Unlike traditional systems, the integration of these power plants at the distribution level enables bidirectional power flow, which can significantly reduce distribution losses [4]. These generating plants, commonly referred to as distributed generators (DG), are connected directly to the distribution feeder or on the consumer side of the meter [5], [6]. Distributed generation has emerged as one of the most promising techniques for meeting the growing power demand in recent years. The integration of DGs offers significant advantages, particularly in mitigating transmission and distribution losses, which represent a substantial financial burden [6].

Generally, DGs have the capability to supply both real and reactive power, effectively reducing the net power consumption seen by the utility due to local self-generation. This reduction in power consumption decreases feeder currents, thereby minimizing network losses and improving voltage profiles [7]. Beyond loss reduction, distributed generation offers additional benefits, including low investment risk, the ability to closely track load variations, and a compact physical size that facilitates easier site availability [5]-[7]. Moreover, the integration of DGs aids in automatically reducing peak energy demand, thereby lessening

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the need to run high-cost thermal power plants during peak hours, ultimately minimizing generation costs [8]. The peak reduction can occur during either day-peak or night-peak periods, depending on the type of DG used.

The capacity of DGs in a given distribution network depends on a number of factors including resource availability, financial feasibility, and constraints of the distribution network parameters. In the meantime, DG capacity can also be determined to get the maximum benefit with due consideration of the abovementioned factors [3]. The location of a DG is critically important since it changes power flow, hence the power losses in the distribution system [9]. Extracting the maximum possible benefits from DG placement is a challenging task. DG capacity and location are the factors that highly influence the end results [12]-[36]. Therefore, careful consideration is required when placing DGs in the distribution network for loss reduction purposes. In the case of some renewable energy sources, location selection will be not applicable due to the site constraints. However, incorrect placement of DGs can lead to higher energy losses than the base case losses [12], [14], [15], [21], [22], [23], [24], thereby reducing the overall benefits of DG placement projects. Numerous researchers have proposed various techniques to determine the optimum location and capacity of DGs from different perspectives. Nevertheless, most of these studies rely on standardized balanced test bus systems, with only a limited number addressing the application of these techniques to real-world distribution systems. Therefore, the primary objective of this research is to bridge the above-mentioned gap by developing a simple & straightforward method for allocating DGs in a practical unbalanced distribution system, considering the constraints imposed by the utility.

2. Review of Existing DG Optimization Techniques

As previously mentioned, the random placement of DGs can worsen power losses, ultimately reducing the benefits of DG placement projects. Many researchers have explored various techniques aimed at determining the optimal capacities and locations of distributed generators, considering a range of objectives and constraints. In general, research related to DG capacity and location optimization can be divided into two main categories, depending on the objectives of the optimization process. The first category is Single-Objective Optimization (SOO) methods, which primarily focus on power loss reduction while considering additional constraints, such as feeder voltage and current limitations. Analytical methodologies and single objective-based iterative nature-driven approaches are typical in this category. Among these various SOO techniques, analytical methods stand out as the simplest and fastest approaches. These analytical methods typically involve fewer equations, derived from theoretical principles, resulting in reduced computational time requirements. This characteristic leads to a better accuracy-to-computational-time ratio.

Lee and Willis (2000) introduced an analytical approach for distributed DG placement, and they showed that the optimal DG capacity should be approximately two-thirds of the incoming generation capacity and that it should be positioned roughly two-thirds along the feeder length [10]. This study represents one of the initial investigations into DG integration, which is applicable only to distribution systems with uniform loading. Building upon this method, Wang and Nehrir (2004) further refined the methodology, introducing diverse approaches for DG integration tailored to different load distributions along the feeder [11]. However, beyond these straightforward theoretical methods, analytical approaches based on the Exact Loss Formula significantly enhance DG optimization. This Exact Loss Formula based analytical methods remain unaffected by load distribution variations, yielding highly precise results, especially for single-objective loss minimization in DG placement problems. As proposed in [12]-[16] this Exact Loss Formula based analytical techniques can be easily utilized to find the optimum DG capacity which gives minimum system losses. Most of the proposed Exact Loss Formula-based DG methodologies have achieved more than a 50% reduction in losses through DG placement [12]-[16].

The Exact Loss Formula represents the total network losses for a given power system and is shown in Equation (1) below [12]-[16].

$$P_{Loss} = \sum_{i=1}^{N} \sum_{j=1}^{N} [\alpha_{ij} \left(P_i P_j + Q_i Q_j\right) + \beta_{ij} (Q_i P_j - P_i Q_j)] \quad \dots (1)$$

and

$$\alpha_{ij} = \frac{r_{ij}}{V_i V_j} \cos(\delta_i - \delta_j)$$

$$\beta_{ij} = \frac{r_{ij}}{V_i V_j} \sin(\delta_i - \delta_j)$$

where,

P_{Loss}	– Total system power losses
$V_i \angle\delta_i$	– Voltage at i^{th} bus
$r_{ij} + j\, x_{ij}$	– ij^{th} element of $Zbus$ matrix
P_i	– Active power injection at i^{th} bus
Q_i	– Reactive power injection at i^{th} bus
N	– Total number of buses

By partially differentiating this Exact Loss Formula with respect to the DG capacity, the optimum point that minimizes losses can be determined. This concept forms the foundation of all Exact Loss Formula-based DG optimization research. Further discussion on this topic will follow in subsequent sections, as the proposed approach in this study is also based on the Exact Loss Formula.

Although these single-objective-based analytical approaches offer notable advantages, they also possess certain limitations. One significant drawback is their inability to handle DG optimization problems with multiple objectives or constraints. These methods typically focus solely on minimizing power losses as the single objective, addressing only power flow-related constraints such as the interplay between power generation, demand, and network losses. When considerations of stability and reliability constraints arise, these approaches alone may not suffice for comprehensive DG optimization procedures.

Apart from the mentioned analytical approaches, nature-driven metaheuristic approaches are also generally used in single-objective DG optimization problems. These approaches are typically involving algorithms inspired by natural processes or phenomena. Several nature-driven approaches are utilized for single-objective DG optimization, including Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Ant Colony Optimization (ACO), and Artificial Bee Colony (ABC) Algorithm [37]. Among these, GA and PSO are particularly prevalent in DG optimization research [17]-[34]. While these approaches generally produce better results, the initial random approximation and iterative nature can sometimes lead to errors in the outcomes [38].

Researchers [17]-[19] have developed Genetic Algorithm (GA) based algorithms aimed at determining the optimal sizes and locations of distributed generators, with the focus on minimizing power loss as the primary objective while also accounting for system constraints. These studies achieved notable success, achieving over a 40% reduction in losses across the considered bus networks. Additionally, Calvachi et al. (2023) introduced a methodology to determine DG capacity and location, prioritizing the enhancement of voltage profiles as the primary objective [20].

Research studies [21]-[26] employed single-objective Particle Swarm Optimization (PSO) for power loss minimization as their primary focus. These investigations achieved significant reductions in loss percentages, surpassing 45% for the chosen bus networks. Notably, both IEEE 33 and 69 bus networks were utilized to showcase the results in studies [22] and [23]. In reference [27], researchers introduced the Loss Reduction Index (LRI) as an alternative to the conventional loss reduction objective. The LRI accounts for both real and reactive power losses, providing a more comprehensive approach. This study demonstrated that the installation of a DG capable of supplying both real and reactive power led to significant reductions in losses. Specifically, the active power loss was reduced by 23.77% compared to the base case.

The second category of DG placement approaches is recognized as methodologies based on multi-objective optimization [39]. In contrast, this category tends to focus more on fulfilling power system planning requirements. Also, these approaches find greater relevance in strategically siting DGs within distribution systems to meet projected future demands while concurrently minimizing losses. Given the need to satisfy a multitude of technical and economic criteria, these optimization processes tend to be more sophisticated, often involving a surplus of objectives and constraints. As a result, most of these DG optimization methodologies exhibit nonlinear characteristics. Nevertheless, they are essential for maintaining the long-term reliability and sustainability of distribution systems, especially in the face of growing energy demands and increasing operational challenges [40]. Nature-inspired iterative metaheuristic algorithms, previously discussed under Single-Objective Optimization (SOO), can also be utilized for multi-objective optimization in DG placement problems. This involves incorporating weighted average sum techniques to combine multiple objectives into a single objective function. Additionally, certain nature-driven approaches inherently offer direct multi-objective optimization capabilities.

The research [28] introduced a Genetic Algorithm-based methodology aimed at optimizing DG capacity and location, considering multiple objectives such as loss reduction, voltage profile improvement, and environmental impact minimization. The effects of each objective were incorporated into the objective function as a weighted sum. Similarly, both [29] and [30] proposed GA-based multi-objective optimization approaches focusing on loss reduction and cost reduction. In these studies, a weighted sum method was utilized to convert multi objectives into a single objective function. PSO-based weighted sum multi-objective optimization approaches were introduced by [31]-[33] to optimize DG capacity and location while addressing various objectives and constraints. In contrast, [34] proposed a Multi-Objective PSO (MOPSO) approach to achieve better results in DG sizing and siting problems without relying on the weighted sum method.

In addition to the metaheuristic approaches, AI methods such as Artificial Neural Networks (ANNs) have been integrated into studies on optimizing DG capacity and location. Research studies [35] and [36] have proposed a combined approach using ANN and PSO for determining DG capacity and location. Specifically, [39] focused on power loss reduction as the sole objective, while [40] considered both power loss minimization and voltage stability enhancement. However, conventional learning algorithms in neural networks often fail to achieve the desired speed in DG placement problems. To address this limitation, combining Artificial Neural Networks (ANNs) with heuristic techniques, such as PSO, has been recommended, as highlighted in [39].

In conclusion, based on the literature review, nature-driven iterative approaches offer the advantage of integrating additional constraints into the optimization problem compared to analytical methods. However, they may not achieve the same level of accuracy as exact loss formula-based analytical approaches. Moreover, outcomes from nature-driven approaches are influenced by the initial random approximation used in the optimization process. While approaches like Artificial Neural Networks (ANNs) show promise, they cannot be solely relied upon in DG optimization problems due to the limitations of conventional learning algorithms, as noted above. Consequently, it can be further concluded that heuristic approaches tend to produce better results when the number of objectives and constraints in the DG optimization problem is high. Conversely, analytical approaches are more beneficial when the sole objective is power loss minimization and computational time is a concern.

3. Consideration of Specific Features of the Real-World Low Voltage Distribution Systems

Most of the existing literature on DG capacity and placement optimization primarily focuses on single-phase equivalents of balanced three-phase test distribution systems [12]-[36]. In contrast, this research aims to apply DG optimization techniques to a real-world unbalanced distribution network, where the asymmetry of loads across phases poses unique challenges. Consequently, careful evaluation of load distribution across each phase is essential to determine the optimal DG placement locations accurately. Moreover, the calculated DG capacity for each phase is heavily influenced by the phase-wise load distribution, making it necessary to adopt a more detailed and precise optimization approach tailored to unbalanced networks [41]. In this study, rooftop solar PV DG placement is specifically considered, which introduces additional complexities, including utility-imposed constraints such as voltage regulation limits, feeder capacity, and permissible levels of DG penetration. These constraints must be integrated into the optimization process to ensure compliance and practical feasibility. This comprehensive approach is critical for achieving an effective and realistic DG placement strategy in unbalanced distribution systems. The existing requirements imposed by the Ceylon Electricity Board (CEB) for rooftop solar DG integration are discussed in the next section.

3.1 Existing Limitations Imposed by the Utility for the Rooftop Solar PV DG Integration in Sri Lankan Distribution Networks

According to the existing guidelines for rooftop DG placement established by the CEB, multiple factors that significantly impact the distribution network are carefully evaluated when approving rooftop solar installations. A primary concern is that the total allowable rooftop solar integration should not exceed 50% of the transformer capacity in terms of net export [42]. Additionally, the utility assesses the feeder voltages after the proposed solar DG is installed, and if voltage limits are violated, the application may be rejected, or the requested rooftop solar DG capacity may need to be reduced. The utility also checks the voltage unbalance after installing the solar DG along the feeder, and if it exceeds 2% at any point of the feeder [43], the proposed solar DG at the requested capacity will not be approved. However, despite these measures designed to address voltage issues, significant challenges related to voltage regulation still persist within the distribution networks. A summary of the technical and regulatory constraints considered during this proposed DG placement study as per the CEB requirements, is provided below.

- Maximum Solar Integration: Net Export up to 50% of the Transformer Capacity [42]
- Maximum and Minimum Voltage Limits: ±6% of the Nominal Voltage [43]
- Maximum Voltage Unbalance: 2% [43]

Apart from these limits, the tap changer position should remain constant during both day and peak times. The DG allocation must be designed to avoid any need for tap changes. This requirement is particularly critical for long-distance feeders, as the tap position on such feeders is generally set at a higher value to mitigate voltage deviations near the feeder end during night peak hours. Also in this study, limits imposed on individual consumers were not taken into account, as the focus was on pole-wise DG integration.

Also, the installation of solar DGs is widely acknowledged to have a significant impact on distribution network losses. Despite this, the CEB does not currently conduct a proper loss assessment when approving solar DG installations. However, improper placement and sizing of distributed generations can negatively impact Sri Lanka's distribution network, potentially leading to higher losses, as emphasized in [44] and [45]. This issue has received limited attention in previous studies on the Sri Lankan distribution network, as distribution losses are less apparent to stakeholders compared to over-voltage concerns. To address this gap, this study incorporates all existing general considerations imposed by the CEB, with a particular emphasis on minimizing network losses.

4. Proposed Methodology

The overall methodology consists of several key steps. Initially, mathematical modelling is performed, where the Exact Loss Formula is reformulated to calculate the optimal DG capacity. Using the derived equation, the optimum DG capacity is determined for each bus. Then, by placing the optimal DG at each bus one at a time, the network power losses are calculated. The bus that yields the minimum active power loss after DG placement is selected as the best location for DG installation, and the corresponding capacity is considered the optimum DG size. This approach is then repeated for each feeder. The methodology is first applied to a test system to verify its effectiveness, and once validated, it will be extended to a portion of the existing distribution network.

4.1 Mathematical Formulation

As previously mentioned, the total active power loss of a distribution system can be represented by the exact loss formula, which is given in Equation 1. By differentiating this formula with respect to DG capacity, the optimal capacity that minimizes system losses can be determined, as shown in Equation (2).

$$\frac{\partial P_{Loss}}{\partial P_{DGi}} = 0; \quad i = 1,2 \dots, N \qquad \dots(2)$$

This method can be used to find the capacity of both active and reactive power sources corresponding to any identified bus. After calculating the appropriate DG capacities for all buses where rooftop PV integration is feasible, the corresponding power losses will be evaluated. The bus that results in the minimum losses can then be selected as the optimal location. This approach is commonly used in studies that employ the Exact Loss Formula for DG optimization purposes. The overall process is structured as follows,

The active and reactive power injection at i^{th} bus can be rewritten as the DG capacity (P_{Gi}) minus power demand (P_{Di}) as shown in the below equations.

$$P_i = P_{Gi} - P_{Di} \qquad \dots(3)$$

$$Q_i = Q_{Gi} - Q_{Di} = kP_{Gi} - Q_{Di} \qquad \dots(4)$$

where,
P_{Di} and Q_{Di} are the active and reactive power demands at the i^{th} bus, respectively.

k = Ratio of reactive power to active power delivered by the DG.

After substituting Equations (3) and (4) to Equation (1), the Exact Loss Formula can be modified as given in Equation (5).

$$P_{Loss} = \sum_{i=1}^{N}\sum_{j=1}^{N}\{\alpha_{ij}\left[(P_{DGi}-P_{Di})P_j + (kP_{DGi}-Q_{Di})P_j\right)] + \beta_{ij}\left[(kP_{DGi}-Q_{Di})P_j - (kP_{DGi}-Q_{Di})Q_j\right)]\} \quad \ldots(5)$$

By obtaining the partial derivative of the modified Exact Loss Formula (5) with respect to the injected real power (P_{DGi}) at a selected bus, Equation (6) can be derived.

$$\frac{\partial P_{Loss}}{\partial P_{DGi}} = 2\sum_{j=1}^{N}[\alpha_{ij}\left(P_j + kQ_j\right) \left(+\beta_{ij}(kP_j - Q_j)\right] \quad \ldots(6)$$

For the minimum losses, the derivative, should be set to zero.

$$2\sum_{j=1}^{N}[\alpha_{ij}\left(P_j + kQ_j\right) + \beta_{ij}(kP_j - Q_j)]=0 \ldots(7)$$

To determine the optimum DG capacity which yields minimum system losses, Equation (7) was simplified and rearranged. The optimum capacity of the DG for a given node is given in Equation (8).

$$P_{DGi} = \frac{\alpha_{ii}(P_{Di} + kQ_{Di}) + \beta_{ii}(kP_{Di} - Q_{Di}) - A_i - kB_i}{\alpha_{ii}\left(k^2+1\right)} \ldots(8)$$

where,

$$A_i = \sum_{\substack{j=1 \\ j\neq i}}^{N}[\alpha_{ij}P_j - \beta_{ij}Q_j]$$

$$B_i = \sum_{\substack{j=1 \\ j\neq i}}^{N}[\alpha_{ij}Q_j + \beta_{ij}P_j]$$

4.2 Optimum Capacity & Location Calculation

After rearranging the Exact Loss Formula as shown in Equation (7), the optimal DG capacity that minimizes power losses can be determined for each bus in the distribution network. The process flow diagram for calculating the optimum DG capacity and location is shown in Figure 1 below.

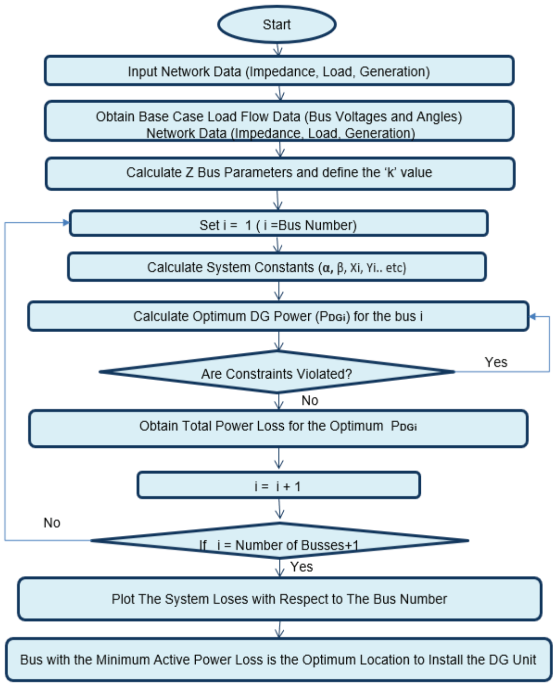

Figure 1 - Process Flow Diagram of Optimum DG Capacity Calculation

Before determining the DG capacity, as illustrated in Figure 1, the factor 'k', which is directly related to the DG power factor, must be defined, as explained in the mathematical modelling section. Research studies [12] and [13] suggested that the DG power factor should align with the load power factor to minimize power losses. However, this approach may not be practical in many real-world scenarios. In this study, the 'k' value was determined based on the power factor of the DG, and the selected 'k' values are provided separately in the two case studies. Additionally, in both case studies, the DG was assumed to operate in a constant power factor mode.

Once the optimum DG capacity for each bus which gives the minimum power loss is calculated, the next step is to identify the optimal location for the DG that minimizes total active power losses. This involves calculating the losses by placing a DG unit with the calculated optimal capacity at each bus, one at a time, necessitating multiple load flow analyses, one for each bus in the system.

5. Results and Discussion

The algorithm for optimizing DG was developed on the MATLAB platform based on the proposed model outlined in the previous section. This algorithm is tested in two cases. In the first case, it is applied to the IEEE 33-bus network to assess the effectiveness of the algorithm in optimizing DG size and location for minimizing power system losses.

In the second case, it was implemented considering a portion of the distribution network in the Kurunegala area of Sri Lanka.

5.1 Case I – IEEE 33 Bus Network

The IEEE 33-bus network is generally modelled as a balanced, single-phase equivalent network for power flow analysis. It is a standard radial distribution test system widely used for load flow studies, optimization problems, and distributed generation placement. In this study, the algorithm was initially applied to the IEEE 33-bus network to benchmark its performance before implementing it on a real-world distribution network.

As described in the methodology, the first step involves obtaining the base case data prior to initializing the algorithm. Some of this base case data serves as the initial input to the main algorithm, while the rest is stored to evaluate the effectiveness of the proposed algorithm by comparing the results before and after placing distributed generation (DG) in the bus network. The base case simulation was done through the Power World simulator and the developed simulation model is shown below.

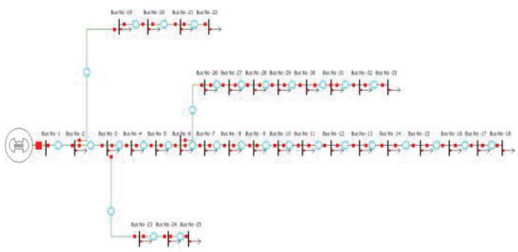

Figure 2 - IEEE 33 Bus Network Simulation Model

According to the base case simulation results, the base active power loss was found to be 211 kW. For the IEEE 33-bus network, the voltage limits were considered in accordance with IEEE regulations, as defined in ANSI C84.1-2020 [46]. Consequently, the nominal operating voltage fluctuation was set at ±5% as per the standard. Based on these voltage limits, 21 buses in the system were identified as low-voltage buses, as their voltages were less than 0.95 pu. After completing the base case simulation, the respective DG capacities were calculated for each bus in the network, assuming a 0.9 power factor for the DGs. Hence the respective 'k' value was defined as 0.48 prior to the DG capacity calculation.

The determined DG capacities for each bus is shown in Figure 3 below.

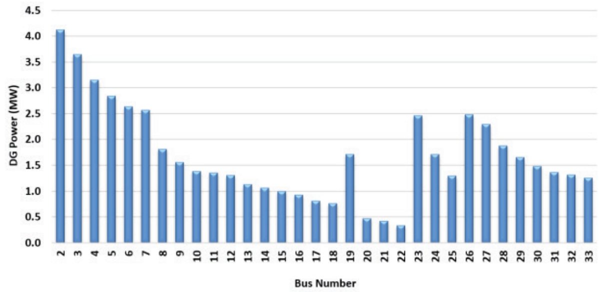

Figure 3 - Calculated Optimum DG Capacities Considering Each Bus in the IEEE 33 Bus Network

As mentioned in section 4.2, once the DG capacities are calculated, the network power losses are determined after installing optimal capacity DGs at the respective buses. The variation in power losses after installing DG in the respective buses is illustrated in Figure 4.

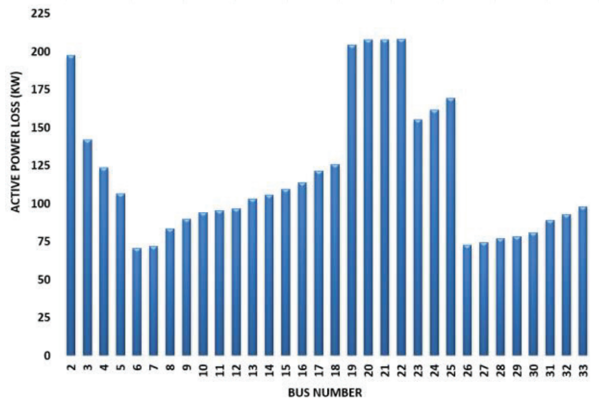

Figure 4 - Variation in Power Losses After Installing DGs in the Respective Buses in the IEEE 33 Bus Network

According to Figure 4, the minimum power loss is achieved when the DG of 2.63MW capacity is installed at the 6th bus. The network's active power losses were reduced up to 70 kW, compared to the initial value of 211 kW. Thus, an approximately 67% reduction in power losses can be achieved by placing the DG with optimal capacity at the most suitable location in the distribution network. The obtained results were then compared with other DG optimization methodologies available in the literature. Table 1 presents a comparison of the effectiveness of the proposed analytical approach against other methodologies. All selected studies used the IEEE 33-bus network for testing, with power loss minimization as the sole objective to ensure an unbiased comparison.

It should be noted that, although this exact loss formula-based analytical method yields a much higher loss reduction percentage compared to other methods available in the literature, when additional objectives beyond power loss minimization and more constraints are introduced, this method alone does not provide a complete framework to solve such complex optimization problems.

Table 1 - Comparison of Results with Other Optimization Methodologies

Optimization Technique	Network Power Loss (After Installing DGs)	Loss Reduction Percentage	Ref.
Genetic Algorithm Based Approach	78.413kW	62.8%	[5]
Particle Swan Optimization Based Approach	110.99kW	47.39%	[6]
Simulated Annealing Based Approach	180kW	15%	[7]
Intelligent Water Drop Algorithm Based Approach	85.78kW	59.3%	[8]
Proposed Approach	70kW	67%	-

5.2 Case II – Distribution Network Portion at Kurunegala Area

The proposed method is subsequently applied to a practical portion of the distribution network in the Kurunegala District. The specifications of the distribution network are presented in Table 2.

Table 2 - Specifications of the Selected Practical Distribution Network

Parameter	Details
Total Number of Consumers	187
Three-Phase Consumers	6
Conductor Type	70 mm² Aerial Bundle Conductor
Number of Three-Phase Feeders	3
Transformer Rating	11 kV/400 V, 160 kVA

In total, there are approximately 78 poles in the network. Although there are three main feeders, the third feeder is lightly loaded; therefore, the methodology was applied only to the first two feeders. As a result, only 50 loaded poles located in Feeders 01 and 02 were considered in the study. The layout of the distribution network is shown in Figure 5.

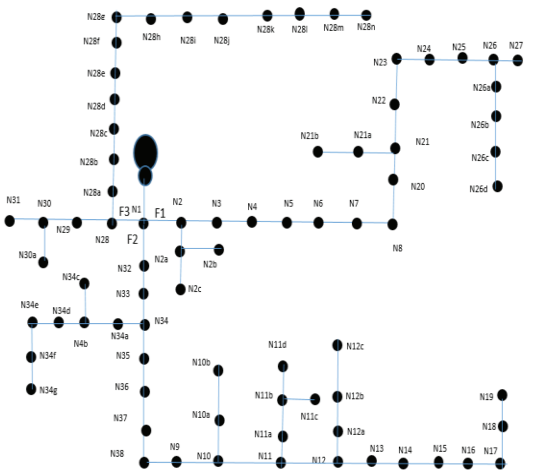

Figure 5 - Pole Arrangement of the Selected Distribution Network

5.2.1 Load Imbalance and its Impact on Solar DG Placement in the Selected Distribution Network

As mentioned earlier, dividing the load evenly among all three phases in practical distribution networks is a challenging task. Most distribution networks in Sri Lanka are inherently unbalanced, resulting in phase voltages that differ from one another. The varying nature of the loads and the connected DGs significantly influence this uneven load distribution across the three phases. This uneven load distribution is evident in the selected portion of the distribution network. The transformer line current curve for this network, observed over a typical day, is shown in Figure 6 and clearly indicates the load imbalance among the three phases.

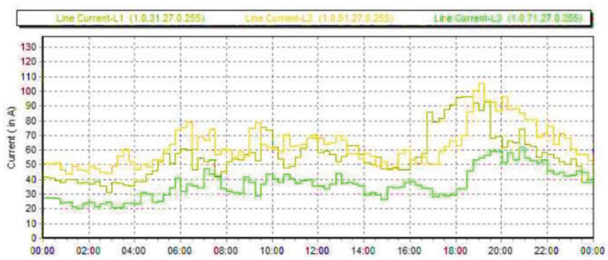

Figure 6 - Transformer Load Current at Each Phase in a Random Day

Based on the collected data, when analysing the average daily load, phase C is consistently less loaded compared to the other two phases. This finding is further supported by the uneven current distribution shown in the Figure 6. Table 3 presents the average load values during the daytime and the average daytime peak load currents for each phase. The average values were calculated using data collected over a one-month period.

Table 3 - Average Load Values and Average Peak Load Currents

Phase	Average Day Time Load (kW)	Average Peak Load Current (A)
A	22.5	80
B	21	70
C	16	50

Figure 7 illustrates the load distribution across the 50 loaded buses for all three phases, further emphasizing the phase unbalance.

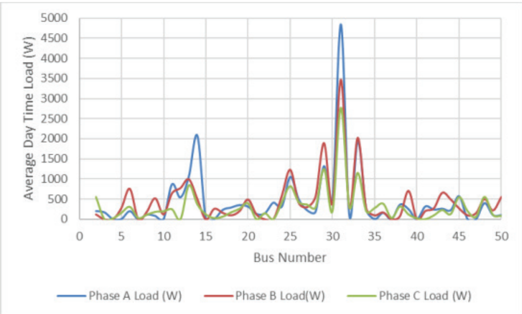

Figure 7 - Load Distribution Among Each Phase

Since the selected distribution network primarily consists of domestic consumers, there are very few high-power consumers on the feeder. Considering the unbalance nature of distribution system, optimal locations and capacities of solar DGs were calculated considering all three phases. Also, to account for future demand, a 10% load increase of the existing daily load was also incorporated.

5.2.2 Loss Sensitivity Factors

Since the network contains a large number of buses, a Normalized Loss Sensitivity Factor (NLSF) was defined to identify optimal locations for DG placement. This factor represents the percentage reduction in the total active power losses of a given feeder resulting from the placement of a small test DG at each bus. To calculate the loss sensitivity at each bus, a test DG unit equal to 3% of the total load of the respective feeder was individually installed at each bus, one at a time. Then the NLSF values for each bus was computed using Equation (9).

$$NLSF_i = \frac{P_{L,Base} - P_{L,test}}{P_{L,Base}} \quad \cdots (9)$$

where,

$NLSF_i$ = Normalized Loss Sensitivity Factor of the i^{th} bus of the feeder

$P_{L,Base}$ = Power loss in the feeder in the base case

$P_{L,test}$ = Power loss in the feeder after placing the test DG at the i^{th} bus

Buses with the highest loss sensitivity factors were identified as candidate buses for solar DG placement. This method effectively reduced the search space, minimizing the computational time required by the algorithm. Based on the calculated NLSF values for each feeder and each phase, Feeder 1 exhibited NLSF values ranging approximately from 0.06% to 0.07%, while Feeder 2 showed values ranging from around 2% to 6%. These results indicate that the variation in loss sensitivity within Feeder 2 was significant, whereas Feeder 1 exhibited minimal variation. Therefore, all buses in Feeder 1 were considered as candidate buses. For Feeder 2, only the buses ranked high in the loss sensitivity factor were selected as candidate buses. Table 4 shows the candidate buses of Feeder 2, and their NLSF values calculated for all three phases.

Table 4 – Selected Candidate Buses in Feeder-2 Based on Loss Sensitivity

Bus Priority Level	Phase A		Phase B		Phase C	
	Bus #	NLSF (%)	Bus #	NLSF (%)	Bus #	NLSF (%)
1	31	5.26	31	6.03	33	4.56
2	32	5.24	32	6.02	34	4.53
3	33	5.20	33	6.00	32	4.53
4	34	5.17	30	5.86	31	4.51
5	35	5.08	34	5.85	35	4.51
6	30	5.04	35	5.77	30	4.36
7	29	4.94	46	5.86	29	4.27
8	46	4.88	29	5.77	46	4.24
9	47	4.81	48	5.51	47	4.22
10	48	4.73	28	5.44	48	4.19
11	28	4.64	47	5.40	28	4.01
12	42	4.60	27	5.20	42	4.01
13	27	4.42	41	5.09	27	3.84
14	41	4.28	42	4.72	41	3.81
15	26	4.00	26	4.70	26	3.46
16	25	3.43	25	4.03	25	2.97

5.2.3 Optimum DG Capacity Determination

Unlike the IEEE 33-bus test system, additional steps were required to determine the capacity and location of DGs in the practical network due to its inherent limitations. One major consideration was the placement of three single-phase solar DGs in the three phases, where the locations of the DGs varied depending on the load distribution. In the case of the IEEE 33-bus network, a single-phase equivalent system was used since the assumption of symmetrical load distribution is valid for that network. Furthermore, the utility-imposed limitations on solar DG integration which are discussed in section 3.1 were also considered when determining the DG capacities and locations.

As mentioned earlier, the selected distribution network consists of three feeders. DG integration was applied only to feeder 1 and feeder 2, as feeder 3 is lightly loaded, and its active power losses are significantly low. From the sensitivity analysis conducted as per section 5.2.2, it was observed that for feeder 1, all buses should be considered for DG capacity determination because the load sensitivity variation across the buses was not significant. However, for feeder 2, candidate buses were selected based on the load sensitivity analysis, and the optimum DG capacities were calculated only for these selected candidate buses across all three phases. The exact loss formula-based methodology, which was mentioned earlier, was then applied to each feeder, considering all three phases. The summary of the calculated DG capacities for each case is given in the Table 5.

Table 5 - Optimum DG Capacities for Each Feeder

	Optimum DG Capacity Range	
	Feeder 01	Feeder 02
Phase A	6kW-6.1kW	12kW-12.5kW
Phase B	5.5kW-6.5kW	14kW-14.5kW
Phase C	3kw-3.5kW	10kW- 10.3kW

When compared to the DG capacities obtained for the IEEE 33-bus network, it was observed that the DG capacities for the feeders in the selected practical distribution network do not show significant variation along the feeder. This is due to the almost symmetrical Z-bus parameters of the feeders in the network. The selected distribution network is constructed using similar types of conductors and relatively uniform line lengths, leading to impedance values that are nearly equal between different buses. However, in a network with significant variations in line lengths between buses, a notable variation in the optimal DG capacities can be observed, which contributes more effectively to reducing network losses.

5.2.4 Determination of Optimum Bus Location

After calculating the DG capacities for each feeder while considering each phase, the losses were determined following the integration of the respective DGs into the system. The variation of active power loss after installing PV-DG at Buses of the respective feeders is illustrated in Figures 7 and 8 below.

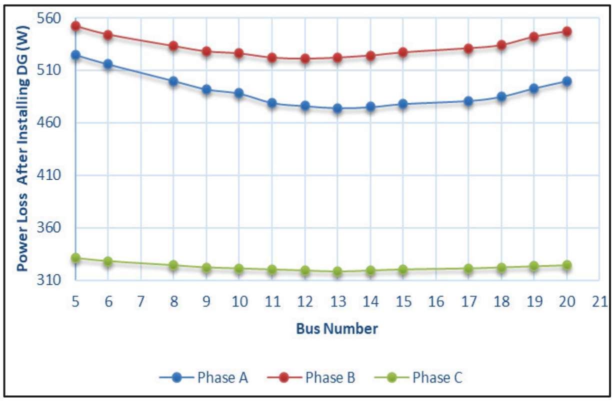

Figure 7 - Variation of Active Power Loss After Installing PV-DG at the Buses of Feeder 01

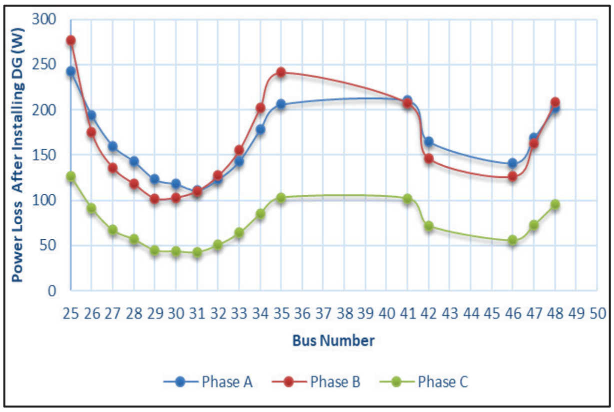

Figure 8 - Variation of Active Power Loss After Installing PV-DG at the Buses of Feeder 02

As illustrated in Figures 7 and 8, the buses that resulted in the minimum power losses were identified as the best candidate buses for DG placement. Consequently, when integrating solar systems into the selected bus network, these buses should be prioritized to achieve maximum reduction in network power losses. A summary of the best candidate buses that yield the maximum network loss reduction is provided in the Table 6.

Table 6 - Optimum Bus Locations Which Yields Maximum Loss Reduction

Phase	Optimum Locations		Base Case Power Loss	Power Loss Reduction (After Installing DGs at Both Feeders)
	Feeder 01	Feeder 02		
A	13	31	565W	545W
B	12	29	590W	558W
C	13	31	344W	315W

As shown in Table 6, the total power loss reduction in the distribution network is considerable at each case and approximately 1.5 kW loss reduction could be done via optimal placement of DGs. Therefore, the daytime technical loss reduction per month is around 400 kWh. Assuming the average per-unit cost during daytime is Rs. 35, it can be concluded that approximately Rs.168,000 in energy costs can be saved annually through the strategic placement of DGs. While the daytime energy consumption of the selected feeder is relatively low, this saving would be significantly higher for feeders with greater energy consumption.

It should also be noted that distribution losses are not limited to feeder power losses. Losses such as transformer losses and energy meter losses account for a significant portion of the total distribution losses. The loss reduction presented in this study focuses solely on feeder power loss reduction. Consequently, the actual loss reduction percentage is somewhat higher than the reported values, as reductions in other loss components after DG placement are not accounted for the calculations.

5.2.5 Impact of Optimal Solar DG Integration on Voltage Profile and Unbalance

Additionally, the integration of solar DGs at optimal locations led to a significant improvement in the overall voltage profile of the bus network. During the DG capacity determination process, voltage constraints imposed by the CEB were carefully considered to ensure compliance with regulatory limits. This approach helped to prevent overvoltage conditions, even under varying load conditions ranging from minimum demand to peak levels. The improved voltage profile during day-peak demand conditions, after the installation of DGs, is illustrated in Figure 9.

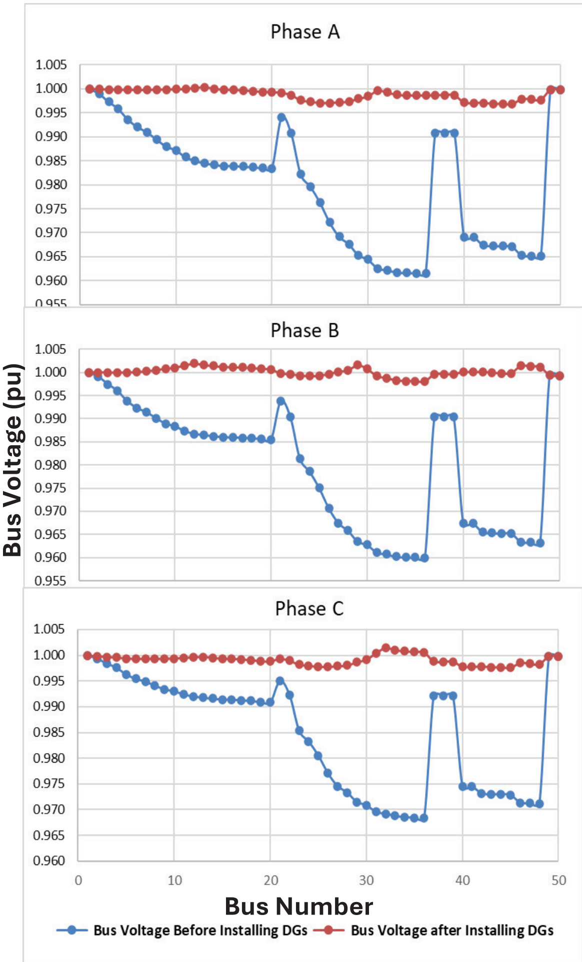

Figure 9 - The peak-time voltage profiles before/after installing DGs

As shown in Figure 9, even before installing the Solar DG, the voltage values of the distribution network were within the recommended voltage limits of Sri Lanka. However, after placing the DGs, a significant improvement in the voltage profile can be clearly observed. Another important factor is that no over-voltages occur within the system, even when the solar DGs operate at full capacity during projected low-load conditions. Hence, it can be concluded that this methodology is highly beneficial for feeders experiencing undervoltage issues. Additionally, it helps suppress over-voltages caused by the improper placement of solar DGs, a common issue in the Sri Lankan distribution network.

The optimal placement of solar DG units in the distribution network not only significantly improves the voltage profile of each phase but also greatly reduces voltage unbalance. Figure 10 illustrates the variation in voltage unbalance before and after integrating the DGs. It clearly demonstrates that the system's maximum voltage unbalance is significantly reduced and remains within the limits imposed by the CEB.

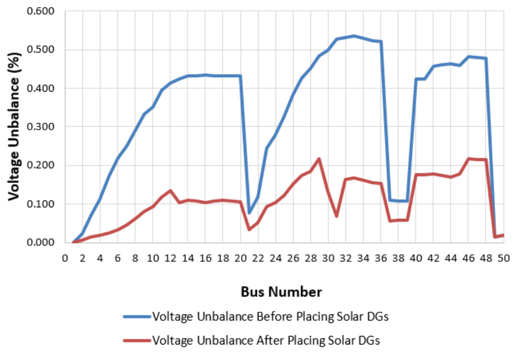

Figure 10 - Voltage Unbalance Variation Before/After Installing DGs

6. Conclusions

This paper proposed an exact loss formula-based methodology to optimize the placement and sizing of DG units within distribution networks. Initially, the proposed methodology was tested on the standard IEEE 33-bus network, and the simulation results demonstrated its effectiveness in reducing power losses within the distribution network through optimal DG placement. The same methodology was then applied to a practical distribution network for placing rooftop solar DGs while considering practical constraints. The results indicated that integrating solar DGs at these optimal locations significantly reduced network power losses, improved the voltage profile, and minimized voltage unbalance, all while ensuring compliance with Sri Lankan low voltage regulation limits. Additionally, the study accounted for the system constraints imposed by the CEB, confirming that overvoltage issues did not occur, even under low load conditions. The results of the case study showed that the loss reduction is 1.5 kW leading to a daytime energy loss reduction of around 400 kWh per month. Assuming the average per unit cost during daytime is Rs. 35, it can be concluded that approximately Rs. 168,000 can be saved per year through the strategic placement of DGs.

Also, it is important to note that distribution losses are not limited to feeder power losses, as transformer losses and energy meter losses represent a significant portion of the total distribution losses. This study focuses exclusively on feeder power loss reduction, implying that the actual loss reduction could be greater than the reported values, as losses in other components affected by DG placement are not accounted for in the calculations. For instance, when the feeder's power demand is adequately met by the DGs, transformer losses decrease since the full power requirement is no longer drawn from the transformer. The other important fact is, the daytime energy consumption of the selected feeder is relatively low, at approximately 34% of the transformer capacity. However, the savings would be significantly higher for feeders with greater energy consumption.

The proposed methodology can be applied from two perspectives. The first is to assess whether a pre-determined DG capacity and location (selected based on other criteria, such as economic factors) is optimal in terms of minimizing power losses. For instance, if the utility receives multiple requests for rooftop solar PV installations at consumer premises, it can evaluate the impact of these requests on distribution losses. This enables the utility to prioritize locations and negotiate with consumers regarding capacity adjustments. The second perspective involves identifying locations that offer maximum benefits when adding a fixed DG to the system. For example, if the utility aims to select a location from several suitable sites (based on factors like land availability), this method can help prioritize locations based on potential power loss reduction. Therefore, this approach provides a comprehensive solution for efficiently integrating rooftop solar DGs, reducing network losses, and mitigating overvoltage and voltage unbalance issues, ultimately enhancing the overall efficiency and performance of the distribution network.

However, the primary focus of the proposed approach is the strategic placement of solar DGs for loss reduction. While the Exact Loss Formula is computationally efficient for single-objective problems, it may encounter challenges when applied to larger, more complex networks or multi-objective scenarios. Future developments could involve integrating the proposed analytical approach with advanced algorithms to incorporate additional objectives and constraints relevant to power system planning. This would enable a more holistic consideration of stakeholder perspectives, further improving the effectiveness of DG placement within distribution systems.

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