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ORIGINAL ARTICLE

Optimizing the Placement of Distributed Renewable Energy Resources in Large-Scale Distribution Systems

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Abstract

The increasing demand for electrical energy has made renewable energy generation sources indispensable in distribution systems. The optimal location and sizing of renewable energy generators (REG) significantly influence system losses in a distribution network. This study presents the Repeated Load Flow (RLF) optimization approach to determine the ideal placement and capacity of various REG types in large-scale radial distribution systems. The primary objective is to minimize power losses through strategic REG placement. The proposed method employs a simple yet effective repeated load flow technique to identify the optimal locations and sizes of REG. The proposed method's performance against existing approaches using a range of case studies, including active power, reactive power, combined real and reactive power, and optimal power factor. Simulation results consistently show our method's superiority. From this study includes key numerical results, such as to 63.60% loss reduction in large-scale distribution systems and an 8.65% improvement in the voltage profile in the best case. Additionally, optimal REG placement enhances network efficiency. The validation of the approach is further confirmed through its application to large-scale distribution test systems.

Keywords Renewable energy generators · Repeated load flow · Power loss · Distribution network · Voltage profile

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1 Introduction

The integration of renewable energy sources into national energy planning has become increasingly essential to address sustainability concerns in the power and energy sector. In many developing countries, the growing gap between electricity generation and demand is being bridged by the widespread deployment of renewable energy generators [1]. As such, the number of REG installed in distribution and sub-transmission networks has witnessed a significant surge. These REG offer numerous technical benefits, including reduced line losses, improved voltage profiles, enhanced reliability and security, and decreased greenhouse gas emissions from central power plants [2]. Moreover, REG help alleviate congestion in transmission and distribution networks. Compared to high-voltage transmission networks, distribution systems often experience significant power losses caused by factors like low load voltages and high load currents. This not only increases the cost of power generation but also results in reduced voltage profiles and other operational challenges within the distribution system [3].

To quantify the benefits of renewable energy generators and determine their optimal penetration levels, various optimization techniques have been employed. These techniques focus on identifying the ideal location and size of REG to improve specific objectives or combinations thereof. Analytical and improved analytical methods have been proposed to optimize the placement and capacity of distributed generations (DGs) for power loss reduction. Additionally [4], has explored optimal sizing and placement of DGs using a simple conventional iterative search technique combined with load flow analysis using the Newton-Raphson method. Existing literature on DG placement primarily focuses on optimizing the location and size of DGs to minimize power losses [5–6]. Many studies employ analytical expressions to calculate optimal DG placement, quantifying their impact on system reliability. However, these studies often overlook the optimal allocation of DGs to specific locations or neglect the consideration of both real and reactive power losses [7–10]. Several approaches have been proposed to address these limitations. Genetic algorithms, particle swarm optimization, and hybrid methods have been employed to determine optimal DG placement and sizing. These methods often consider technical objectives, such as minimizing losses and improving voltage stability [11, 12]. However, few studies have integrated DG placement with network reconfiguration or considered the simultaneous optimization of DG and capacitor placement for voltage improvement. Additionally, the identification of weak nodes in radial distribution networks is crucial for effective DG placement. Voltage stability index has been used to identify such nodes. Furthermore, researchers have explored the impact of different load models on DG planning in distribution networks [13]. While significant progress has been made in DG placement optimization, further research is needed to address the challenges of integrating DG placement with network reconfiguration, optimizing both DG and capacitor placement, and considering the impact of various load models [14–19]. A zonal-based pricing method is introduced in [20–23] to determine the optimal location and size of distributed generators (DGs). Another study presented a market-simulation approach to explore the effects of DGs on transmission-expansion planning. Previous research has explored various methods for optimizing the location and size of PV-DGs in distribution systems. Ref [24]. has proposed a probabilistic approach to determine the optimal PV-DG size while minimizing active power losses and ensuring power quality while [25] has utilized differential evolution to find the optimal placement of PV-DGs focusing on reducing total real power loss and improving voltage profiles. Ref [26]. has introduced a loss sensitivity factor simulated annealing method for optimal DG placement and sizing in large-scale distribution systems, aiming to reduce network power losses and enhance voltage stability, while [27] has further improved the tabu search algorithm for loss minimization in large-scale distribution systems. A continuation power flow analysis for DG placement as been proposed in [28]. Additionally [29], has suggested using a feedforward artificial neural network to identify the optimal location and size of DGs with their method tested on a 52-bus system. However, there is a noticeable lack of approaches focusing on the optimal allocation and sizing of DGs specifically for voltage improvement in large-scale radial distribution networks [30–33]. Existing methods for optimizing REG placement often neglect the interconnectedness of factors such as single or multiple REG, power factor, and capacitor placement [34, 35]. This limitation necessitates a more holistic approach. To address this, this paper proposes a novel repeated load flow (RLF)technique. This approach efficiently determines optimal REG locations, sizes, and capacitor placements while enhancing voltage profiles. The proposed technique aims to reduce real power losses in the distribution system while ensuring that bus voltages remain within the acceptable range of 0.95 to 1.05 p.u. To achieve this, the proposal first performs a base case load flow analysis without any REG in the system to establish a baseline for losses. Then, it gradually increases the size of a REG located at bus 1 and observes the resulting losses. This process is repeated for each bus to determine the optimal location and size for minimizing system losses. The performance of the proposal is validated for two large IEEE 69 and 118-bus radial distribution test systems. This work is unique in considering five different REG placement scenarios for optimal location and sizing. The studies show an effective REG placement by the proposal which reduces the load on central generation, improves the utilization of transmission and distribution networks, and significantly reduces power losses. A novel Repeated Load Flow method has been developed for optimizing the placement and sizing of REGs in large-scale radial distribution networks. This efficient approach optimizes both real and reactive power injections simultaneously to minimize network losses. A detailed comparative analysis of various case studies has also been conducted, highlighting the superiority of the proposed method in terms of loss reduction and voltage profile improvement. The study identifies the most suitable bus locations for REG placement, offering valuable insights for power system operators. The revised manuscript now includes a dedicated section that clearly outlines these contributions. A new "Contributions" subsection has been added, emphasizing the innovative aspects of this research in a point-by-point format. The key contributions are as follows:

1. Development of the RLF-based optimization method for efficient REG placement.
2. Simultaneous real and reactive power optimization for loss reduction and voltage stability.
3. Validation of the method using multiple case studies in large-scale distribution networks.
4. Comparison with existing methods, demonstrating superior performance in power loss reduction.

This paper is organized to provide a thorough overview of the proposed optimization technique for the placement and sizing of REGs in distribution networks. It incorporates a literature review that highlights recent studies and identifies gaps in existing methodologies that the proposed approach aims to address. Section 2 defines the problem system, including mathematical formulations for key parameters such as active and reactive power, combined real and reactive power, and the power factor. Section 3 presents the proposed methodology, outlining the iterative process and the use of finer step sizes to enhance accuracy. Section 4 discusses the results of the optimization and sensitivity analysis, demonstrating the method's effectiveness in reducing power losses and improving voltage profiles. Finally, Sect. 6 concludes with a summary and suggests directions for future work, including the exploration of cost-based optimization for REG placement.

2 Problem Formulation

The proposed optimization objective is to minimize real power losses in the distribution system while considering the optimal size and location of REG. The RLF technique is employed to identify the minimum loss configuration. For an n-bus system, we formulate the minimization problem as presented in some previous studies [32, 33]. This formulation aims to minimize total active power losses (PLoss) while considering REG placement. The optimization process is subject to various constraints, including current limits, voltage limits, real and reactive power flow restrictions, and other operational constraints.

$$Min\left\{P_{Loss}=\sum_{r=1}^{nb}I_r^2R_r\right\} \tag{1}$$

The subject to the following generation and voltage constraints:

$$0\leqslant P_{REG}\leqslant\sum P_{load} \tag{2}$$

$$V_{r\ \min}\leqslant V_r\leqslant V_{r\ \max}\ r\ =\ 1,\ 2,\ldots n \tag{3}$$

$$\text{where, } V_{r\min}=\ 0.95\ p.u.\ and\ V_{r\max}=\ 1.05\ p.u. \tag{4}$$

As per above equations represents parameters, such as the number of branches (nb), receiving node (r), the receiving end line current (Ir) number of buses (n) and resistance of line ( ), energy generation (PREG), active power (PLoss). The optimizing REG and capacitor placement is crucial to minimize power losses, costs, and improve efficiency. This study aims to minimize PL during peak load while adhering to voltage and current constraints. The allocation of blended REGs and capacitors in distribution networks, along with their optimal placement, is crucial. Improper allocation can lead to increased power losses, higher operating costs, and reduced system efficiency. The primary objective of the proposed study is to minimize the total real power loss (PL) during peak load conditions in the distribution system, as outlined in Eq. (1), while adhering to the equality and inequality constraints in Eq. (2) and Eq. (3). Regarding the placement of REGs, the voltage at various buses must be maintained within appropriate limits to ensure the reliable and safe operation of the power distribution system. Additionally, the current flow in the line conductor should remain within permissible limits.

3 Proposal

The Voltage drop in a power system is affected by the resistance and reactance of network lines. While transmission lines have a higher reactance compared to resistance, distribution systems have a lower reactance. Capacitors are commonly used in transmission lines to counter the effects of reactance, improving voltage quality and system efficiency.

However, by providing localized support for both real and reactive power, reactive energy generators (REG) can effectively reduce voltage drop and further enhance system performance.

3.1 REG Placement

The integration of REGs will be explicitly modeled to demonstrate their effectiveness in reducing voltage drop and enhancing system performance. Furthermore, new equations have been added to provide a more comprehensive definition of the optimization problem, ensuring a more rigorous formulation. This includes detailed mathematical steps that clarify the modeling approach and solution methodology for optimal REG placement and sizing, thereby improving transparency and reproducibility. Buses in the power system can be prioritized based on their likelihood of experiencing voltage instability, a condition that may result in system failure [31]. This prioritization can then be used to identify the most strategic locations for placing REG to enhance system stability [34]. As an example, a simple two-bus network is shown in Fig. 1a without REG and in Fig. 1b with REG included.

For the two bus network losses in line shown below

$$P_e = JQ_e = I_r^2((R + Jx) \tag{5}$$

Where Pe represents active power loss, Qe denotes reactive power loss in line, R is the resistance, x is reactance of the line, and Ir is the receiving end line of the current. For the two-bus network shown in Fig. 1a, the complex power can be expressed as:

$$S_D = P_D + JQ_D = V_r I_r^* \tag{6}$$

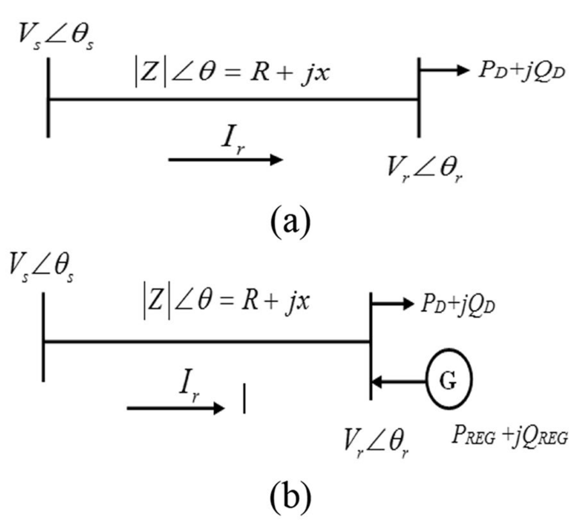

Fig. 1 Schematic illustration of a simple two-bus network: (**a**) without REG, (**b**) with REG

$$S_D = P_D - JQ_D \tag{7}$$

$$I_r = \frac{P_D - JQ_D}{V_r^*} \tag{8}$$

After the enclosure of REGs as shown in Fig. 1b, the receiving end current reduces as.

$$I_r = \frac{(P_D - P_{REG}) - J\,(Q_D - Q_{REG})}{V_r^*} \tag{9}$$

The real power loads (PD), renewable energy generation (PREG), reactive power loads (QD), and renewable energy generation (QREG) are shown above. Vs and Vr represent the sending and receiving end voltages, while θs and θr are the sending and receiving voltage angles, respectively. Z denotes the line impedance, and V_r^* is the conjugate of the receiving end voltage.

3.2 Optimal Location and Sizing of REG

Once the ideal location for REG is determined, their optimal size must be calculated. This is achieved by finding the REG size that minimizes total system power loss, as defined by (1). To optimize REG placement and sizing, their real power injection is varied from 0 to 100% of the total load in increments, ensuring adherence to voltage and generation constraints of (2)-(4). The accuracy of this approach hinges on the step size chosen [37]. This study uses the RLF method with a step size of 0.1 MW.

Initially, a backward-forward sweep load flow analysis is conducted without any REG to establish the baseline system behavior under normal operating conditions. Then, the initial power factor is chosen and a starting bus location is selected where REG will be installed. Incrementally the size of the REG is adjusted in small steps while calculating the losses for each size and performing the backward-forward sweep load flow for each case.

The solution that results in the minimum loss, including the power factor, bus location, and REG size are recorded. This minimum loss is finally compared with the previously recorded losses; if the new loss value is lower, the solution is updated. The algorithm then moves to the next bus location to install REG there and repeat the process. After completing the steps for the power factor, the power factor is slightly increased and the process is repeated from the beginning with the new value. Figure 2 shows the flowchart of the proposal for locating and sizing REG.

The study takes into account the selection of step sizes based on the loss reduction technique, ensuring the system performs optimally. It explains how finer step sizes can improve accuracy while still striking a balance between computational efficiency and precision. A sensitivity analysis has been included to show that reducing the step size (e.g., from 0.1 MW to 0.01 MW) leads to more precise capacity selection for REGs, further boosting system performance by effectively minimizing voltage drop. Additionally, the iterative process has been enhanced with a final adjustment phase to correct any deviations in the optimal capacity values, improving the overall robustness of the optimization method. These updates add clarity and strengthen the reliability of the proposed approach, as demonstrated in Fig. 2, which illustrates the flowchart of the proposed algorithm.

3.3 Multiple REG Location

The method for determining the optimal location of a single REG can be expanded to accommodate multiple REG in a power system, with the goal of minimizing total real power loss while adhering to all system constraints. In this study, it is assumed that each bus can only have one REG. The process involves sequentially fixing one REG at a time, calculating the resulting real power loss and voltage profile for all buses. By repeatedly fixing different combinations of one, two, and three REG, the overall system loss and voltage profile can be evaluated.

4 Numerical Analysis

This work encompasses five distinct scenarios (i.e., case I to case V), each representing a different REG capability, as listed in Table 1.

4.1 69-bus Test Radial Distribution System

The proposed algorithm is first tested on a 69-bus radial distribution network, consisting of 69 buses, 68 branches, and operating at a nominal voltage of 12.66 kV, as depicted in Fig. 3. The network has a total active and reactive power demand of 3802.1 kW and 2694.6 kVAR, respectively. All loads were assumed to be constant. The proposal is developed in MATLA Bversion 2009a on an Intel Core 2 Duo PC with a 2.20 GHz processor and 3 GB of RAM while a Backward-Forward sweep load flow method, also coded in MATLAB is employed to calculate voltage magnitudes, phase angles, line flows, and losses. Five cases introduced in Table 1 are considered to evaluate the algorithm's performance.

4.1.1 Case-I: Injecting Real Power in REG

Without REG, the total real and reactive power losses are225 kW and 102.53 kVAR, respectively. The minimum voltage at a bus is0.90942 p.u. When REG are placed in Case I, the total real and reactive power losses decrease respectively to 83.936 kW and 152.43 kVAR while the minimum voltage increases to 0.96318 p.u. In Case I, five buses (i.e., bus 61, 62, 62, 60, and 64) are identified as optimal locations for REG with ratings of respectively 1.9, 1.8, 1.8, 1.9, and 1.6 MW. The corresponding optimal power losses become83.936, 85.457, 87.635, 92.08, and 97.272 kW. The optimal loss and size of REG are shown in Figs. 4 and 5. The improvement in voltage profile achieved by using REG compared to the base case without REG is illustrated in Fig. 6. The preliminary optimal REG location is determined to be bus 61, with an associated optimal loss of 83.936 kW and an optimal size of 1.9 MW. The improvement in voltage profile becomes approximately 5.58%, with a minimum voltage of 0.96318 p.u.

4.1.2 Case-II: Injecting Reactive Power in REG

In the base case without REG, the total real power loss is 225 kW. When a REG isplaced at bus 61 in Case II, the optimal real power loss becomes 152.43 kW. The optimal size for this REG is 1.3 MVAr, as shown in Figs. 7 and 8. Figure 9 shows improved voltage profiles with a minimum of 0.9305 p.u. at bus 65.

4.1.3 Case-III: Injecting Reactive and Real Power at Power Factors

Six different power factors were considered: 0, 0.5, 0.8, 0.82, 0.9, and 1.0. The power loss associated with each power factor is illustrated in Fig. 10. For the corresponding power factors, the optimal power losses were found to be 152.43 kW, 55.13 kW, 24.312 kW, 24.217 kW, 28.924 kW, and 83.936 kW, respectively. Additionally, the optimal REG size is determined to be 1.3 MW, 2.1 MW, 2.2 MW, 2.2 MW, 2.2 MW, and 1.9 MW, respectively, with the preliminary optimal location consistently at bus 61, as shown in Figs. 11 and 12. Bus 61 is the optimal location for the REG, with a minimum loss of 24.217 kW and an optimal size of 2.2 MVAR at a power factor of 0.82. The voltage profile significantly improves with the installation of the REG, as shown in Fig. 13.

4.1.4 Case-IV: Injecting Real and Reactive Power Associated with Case-I & Case-II

The enhanced voltage profile achieved with the use of REG is illustrated in Fig. 14. This improvement is superior to the results obtained in individual Case I and Case II.The proposed method achieved a total real power loss of 24.346 kW. Bus 61 is the optimal location for the REG, with an optimal active power size of 1.9 MW and an optimal reactive power

Fig. 2 Flowchart of proposed algorithm

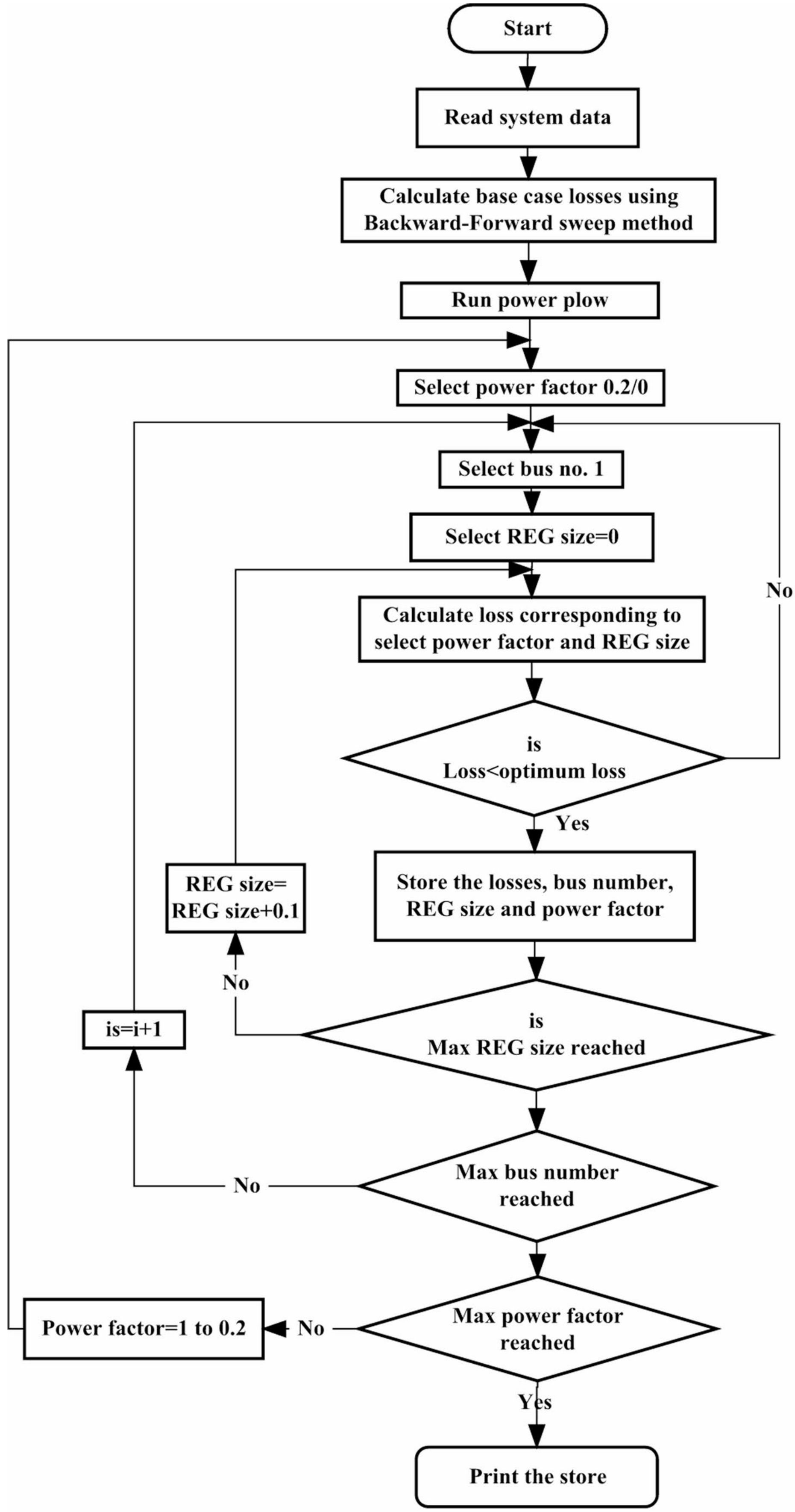

Table 1 REG capability as per the analysis encompasses five distinct scenarios

Case	Injecting Mode/ REG Capability
I	Real Power
II	Reactive Power
III	Both Reactive & Real with PF
IV	Real And Reactive Power
V	Multi Real Power

size of 1.3 MVAr. As a result of installing the REG, the minimum voltage profile improved to 0.96764 p.u.

4.1.5 Case-V: Injecting Real Power with Multi REG

For the three REG, the optimal locations were determined to be buses 61, 16, and 50. The corresponding minimum losses were 83.936 kW, 72.023 kW, and 70.509 kW, respectively.

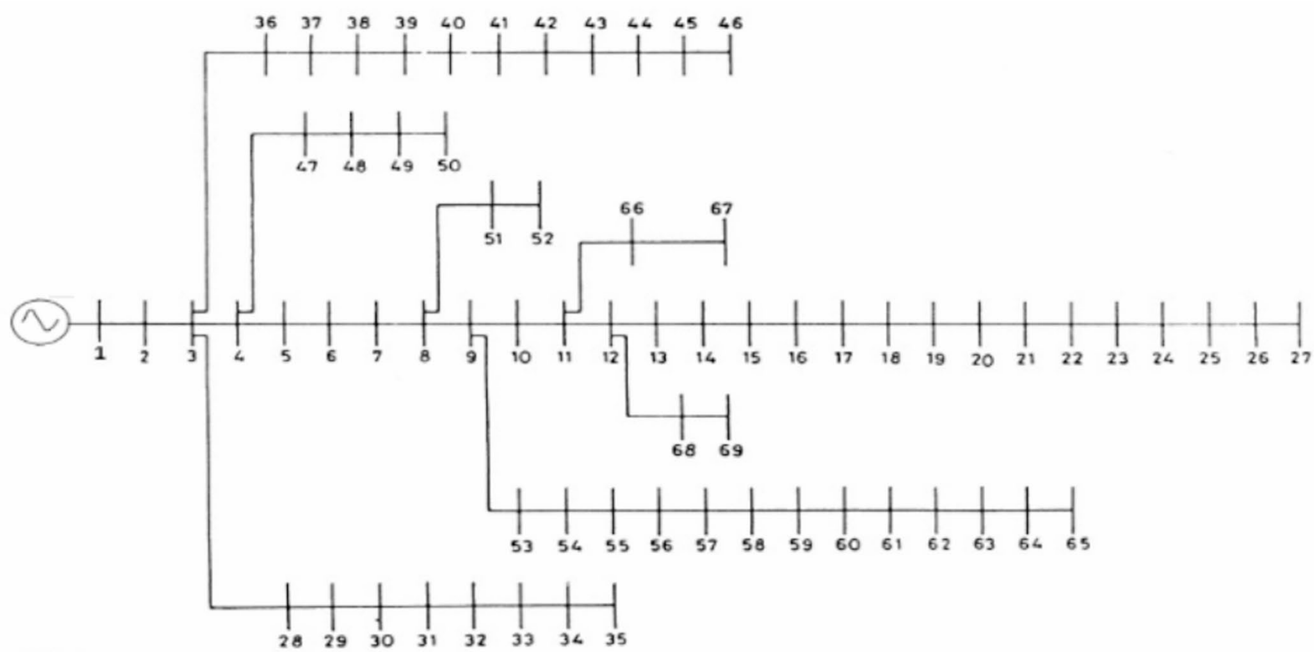

Fig. 3 The 69-bus test system

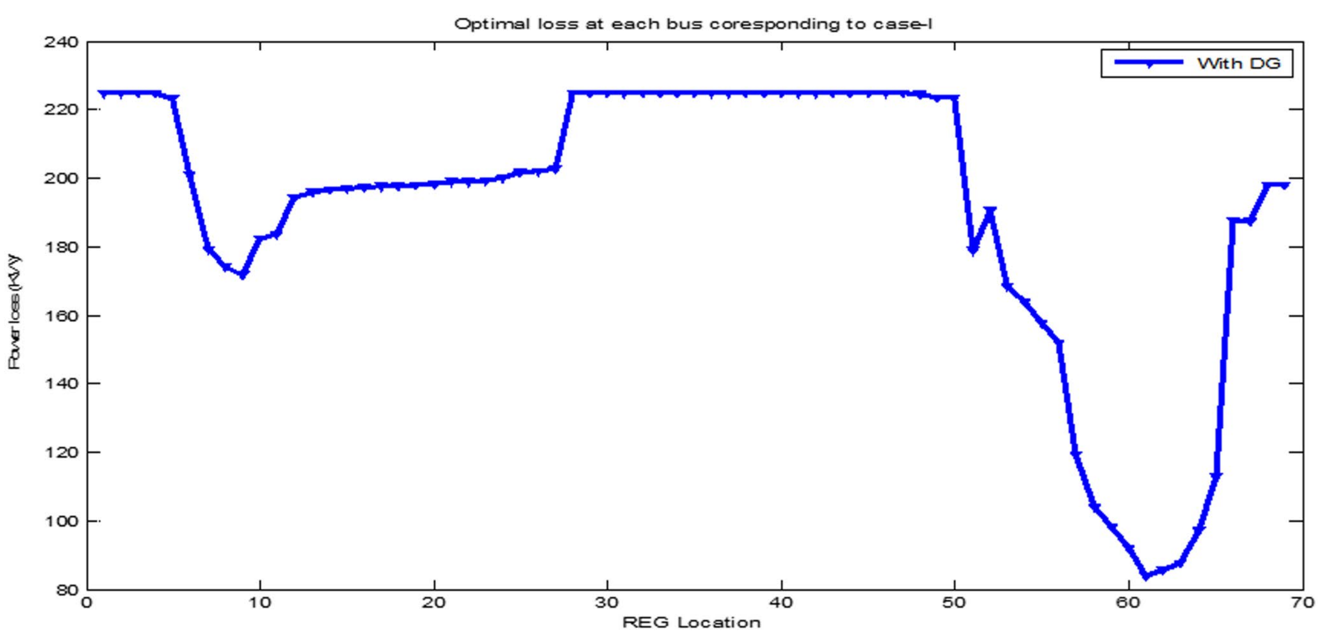

Fig. 4 The losses at each bus

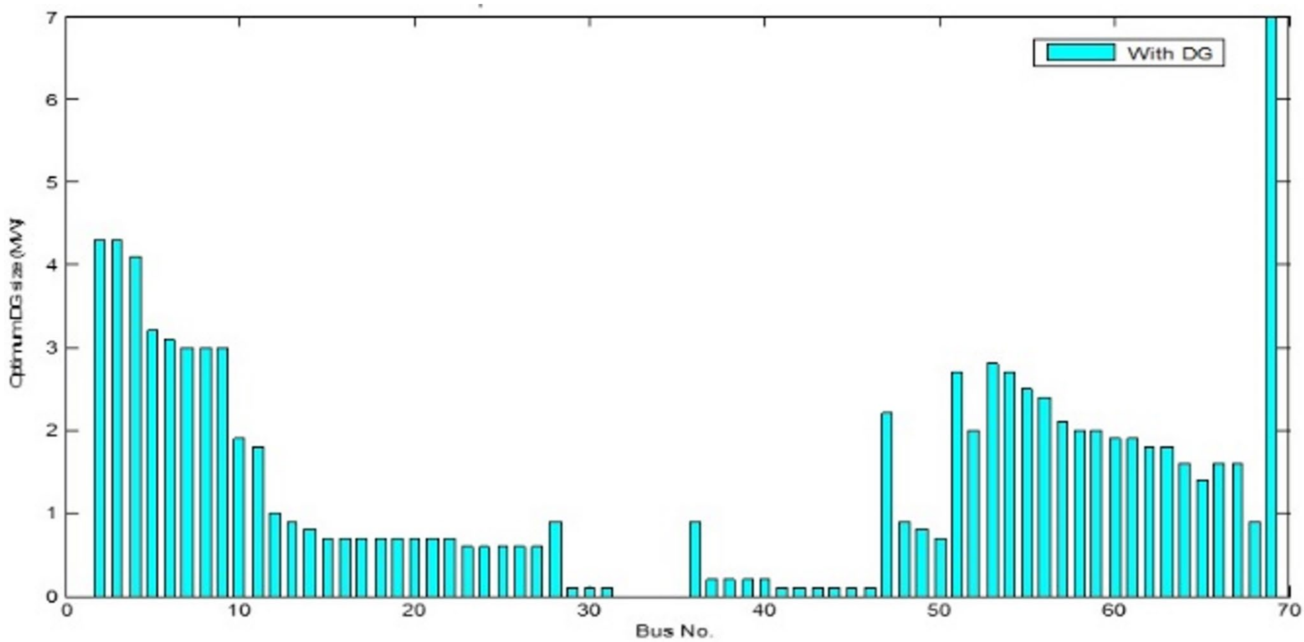

Fig. 5 The size of REG at each bus

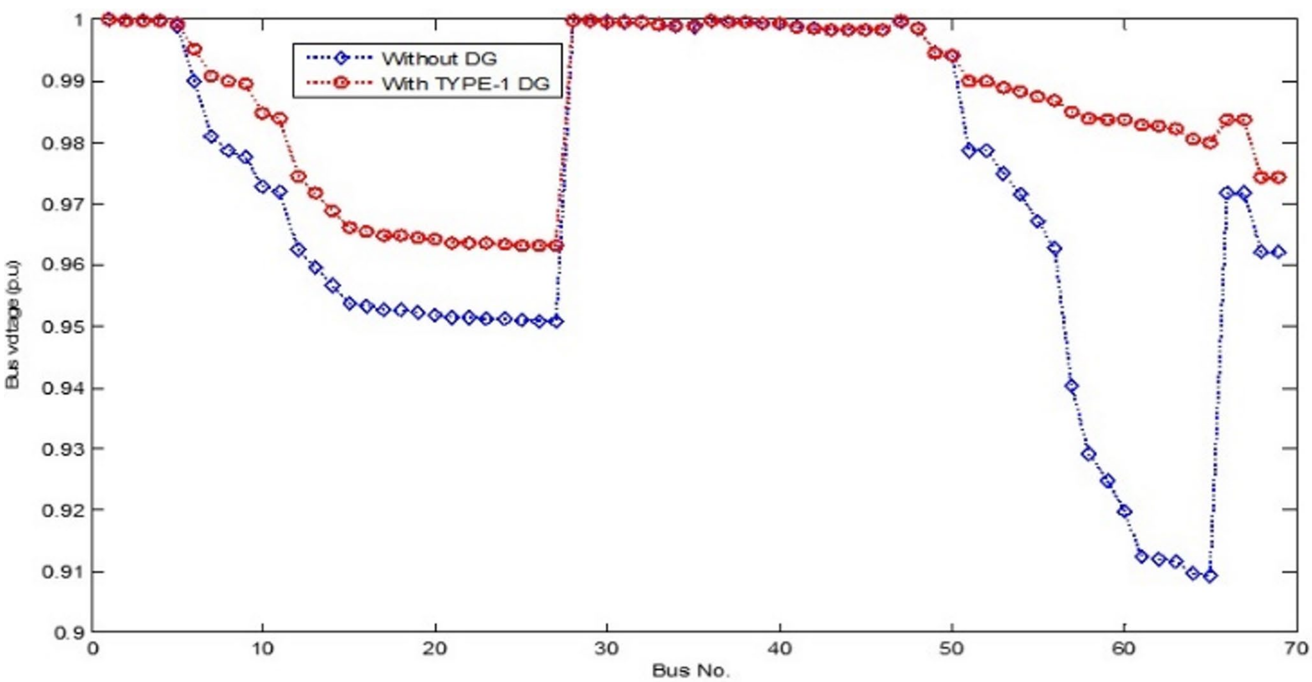

Fig. 6 The comparison with and without REG (Variation in voltage) at each bus

The optimal REG sizes for these locations were 1.0 MW, 0.5 MW, and 0.7 MW, as shown in Figs. 15 and 16. Additionally, when combining the first and second REG at buses 61 and 16, the optimal sizes were determined to be 1.9 MW and 0.5 MW, respectively. This combination resulted in a power loss of 72.023 kW and a voltage profile improvement of 0.91271 p.u. Furthermore, placing all three REG at buses 61, 16, and 50 jointly yielded optimal sizes of 1.9 MW, 0.5 MW, and 0.7 MW, respectively. The corresponding power loss is70.509 kW, and the voltage profile improves to 0.90943 p.u., as shown in Fig. 17.

Table 2 summarizes the results for Case I to Case V. The proposed RLF approach is successfully applied to a large-scale 69-bus radial distribution system. The results for each

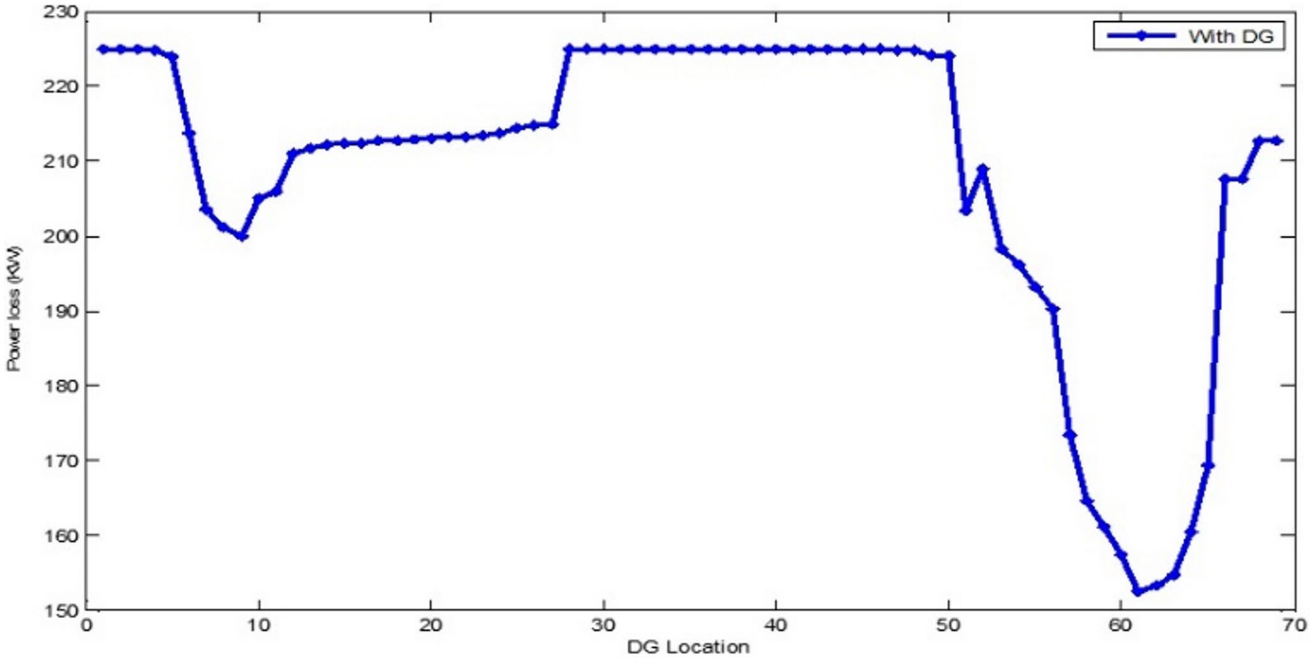

Fig. 7 The loss at each bus

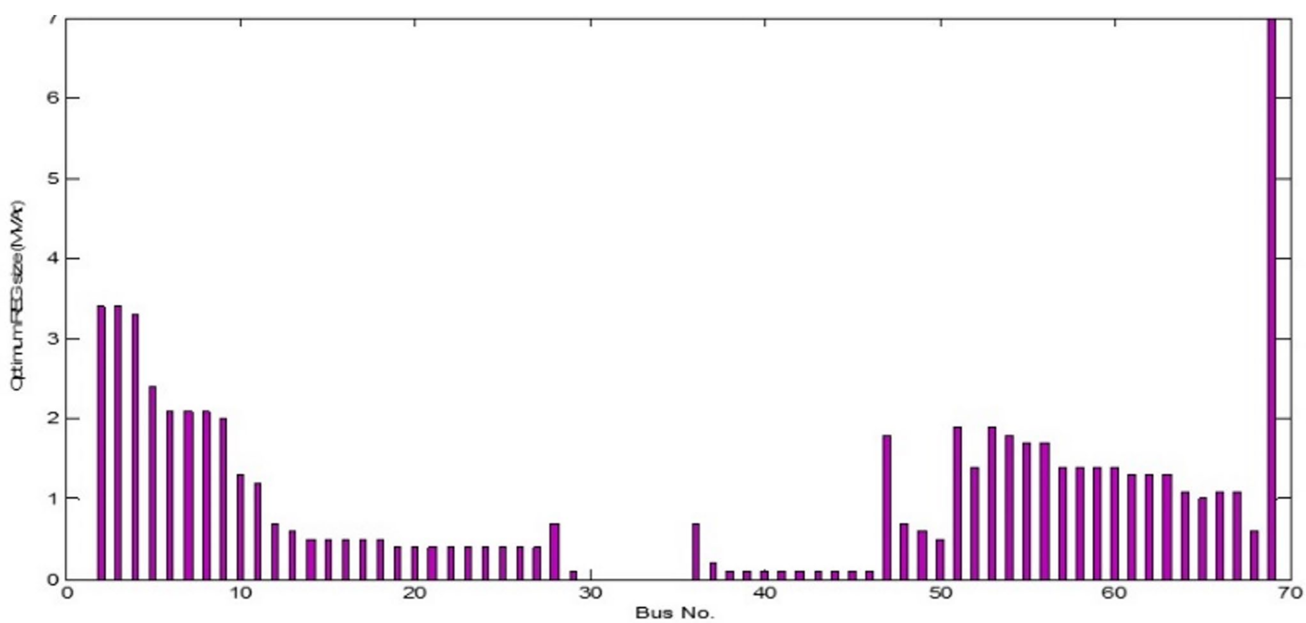

Fig. 8 The size at each bus

case, including the placement and sizing of REG, are presented in Table 2.

Among Cases I to V, Case IV achieved the highest loss reduction of 89.18% and the greatest voltage profile improvement of 6.01%. Case III also performed well, with a minimum loss of 89.24% and a voltage profile improvement of 5.94%. The other cases, I, II, and V, had loss reductions of 62.70%, 32.25%, and 68.66%, respectively, and voltage profile improvements of 5.58%, 2.26%, and 0.01%, respectively.

Clearly, Cases IV and III demonstrate the most significant benefits of REG installation, offering both substantial loss.

reduction and notable voltage profile improvements.

Therefore, the combined bus location at 61 is the most suitable placement for REG in the 69-bus test distribution network.

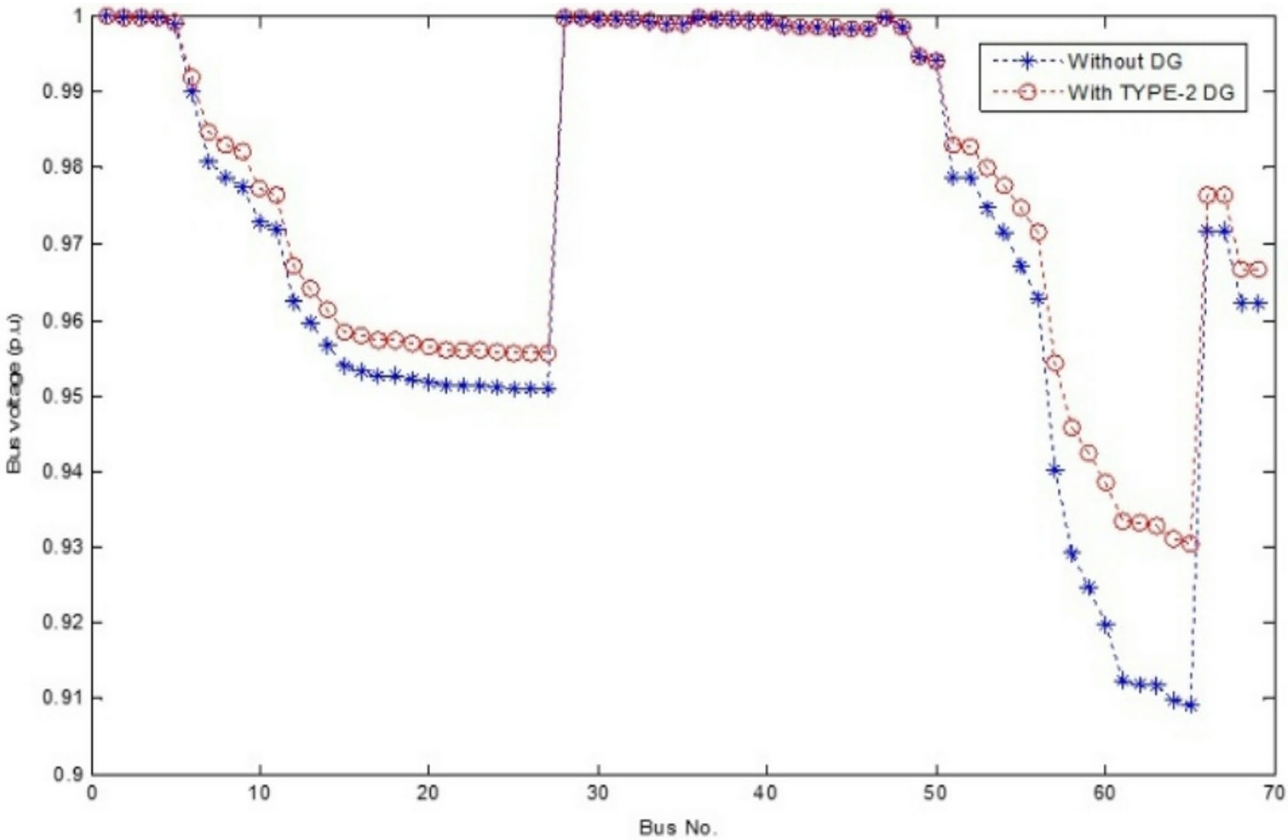

Fig. 9 The Voltage Variation with and without at each

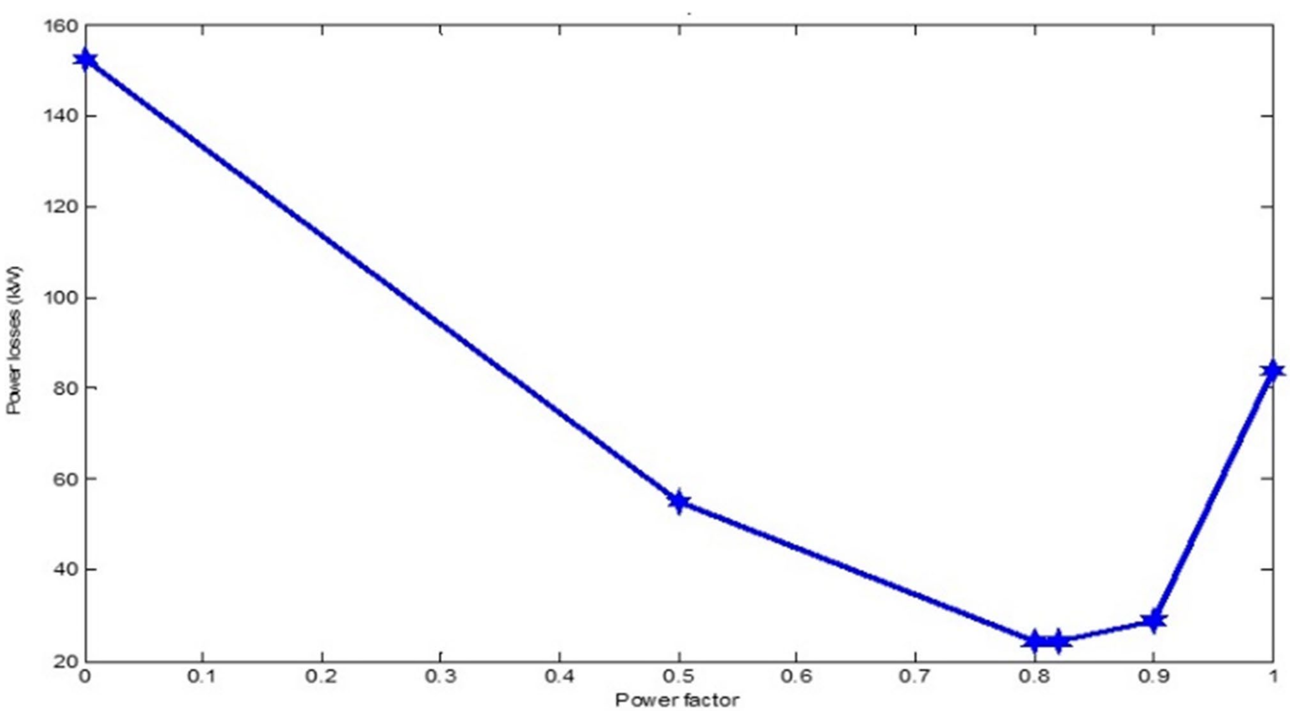

Fig. 10 The real power losses as per the all-power factors

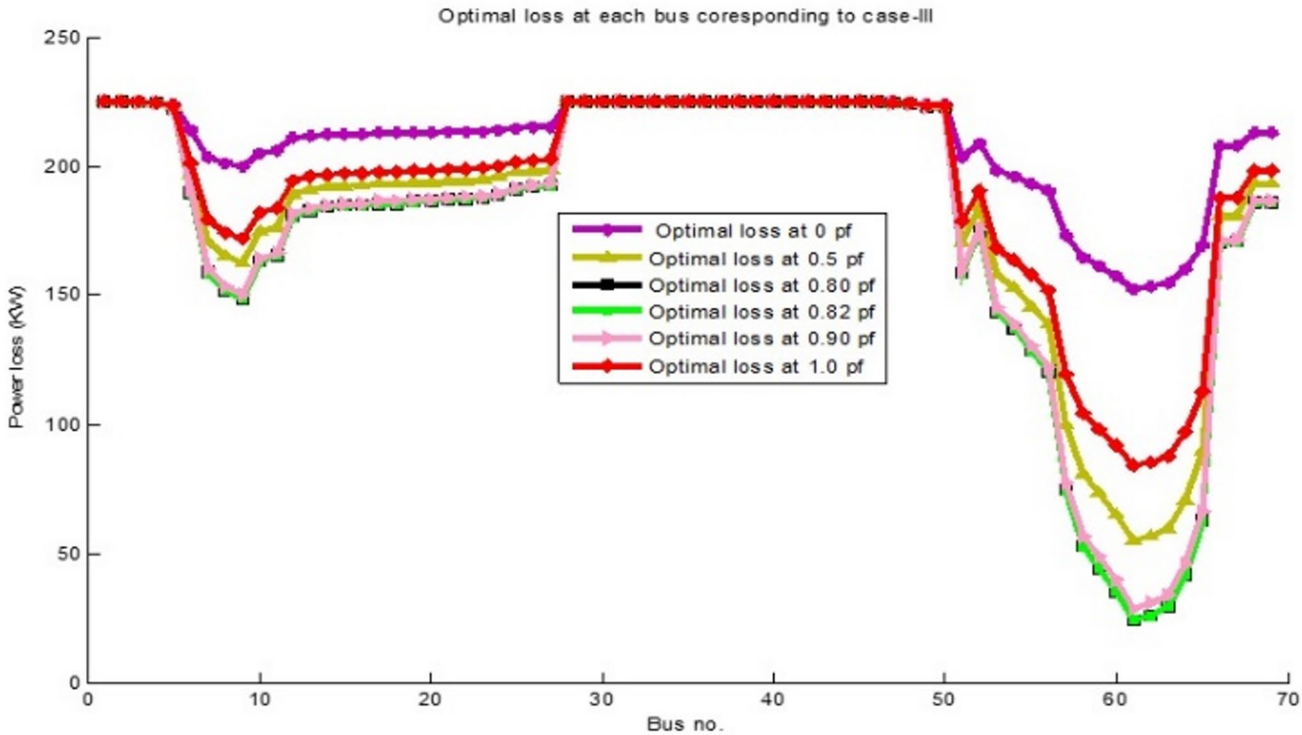

Fig. 11 The Power loss at each bus (69-bus system)

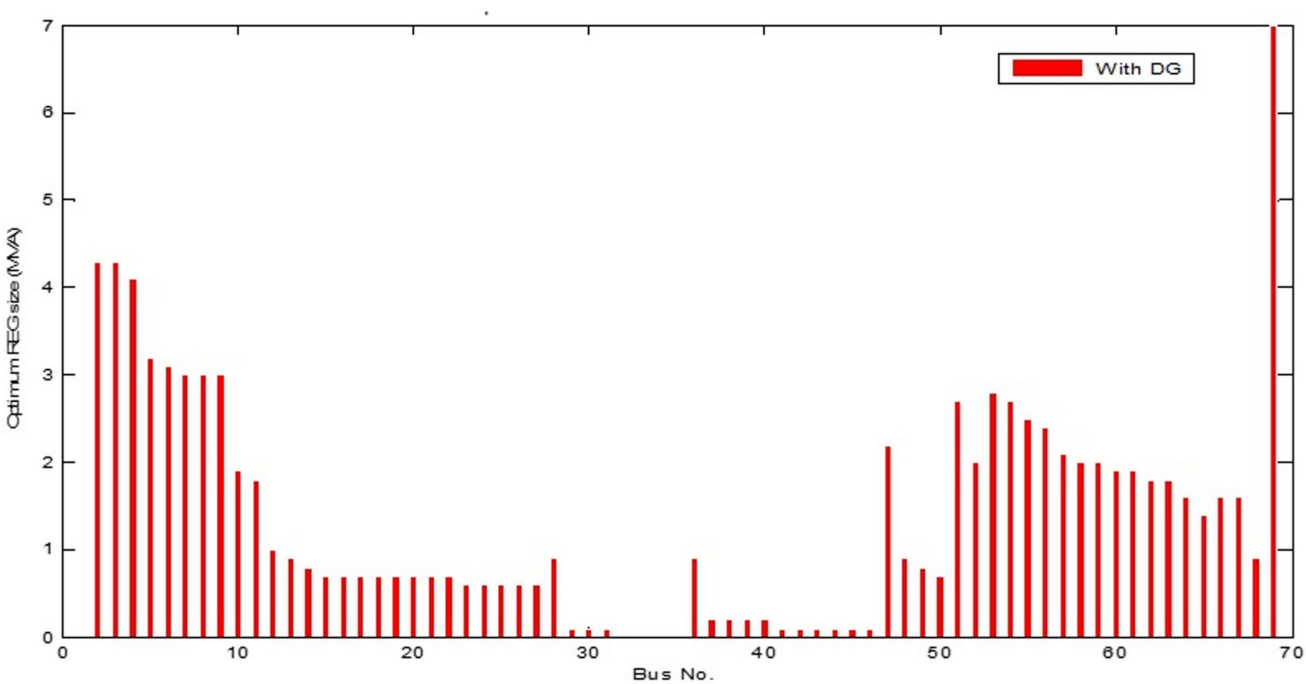

Fig. 12 The size at each bus (69-bus system)

Table 3 compares the proposed RLF approach with other techniques. The RLF approach achieved a loss reduction of 68.66%, outperforming the methods presented in Refs [36–40]. This indicates that the proposed approach is an effective and efficient solution for REG placement and sizing in power distribution systems.

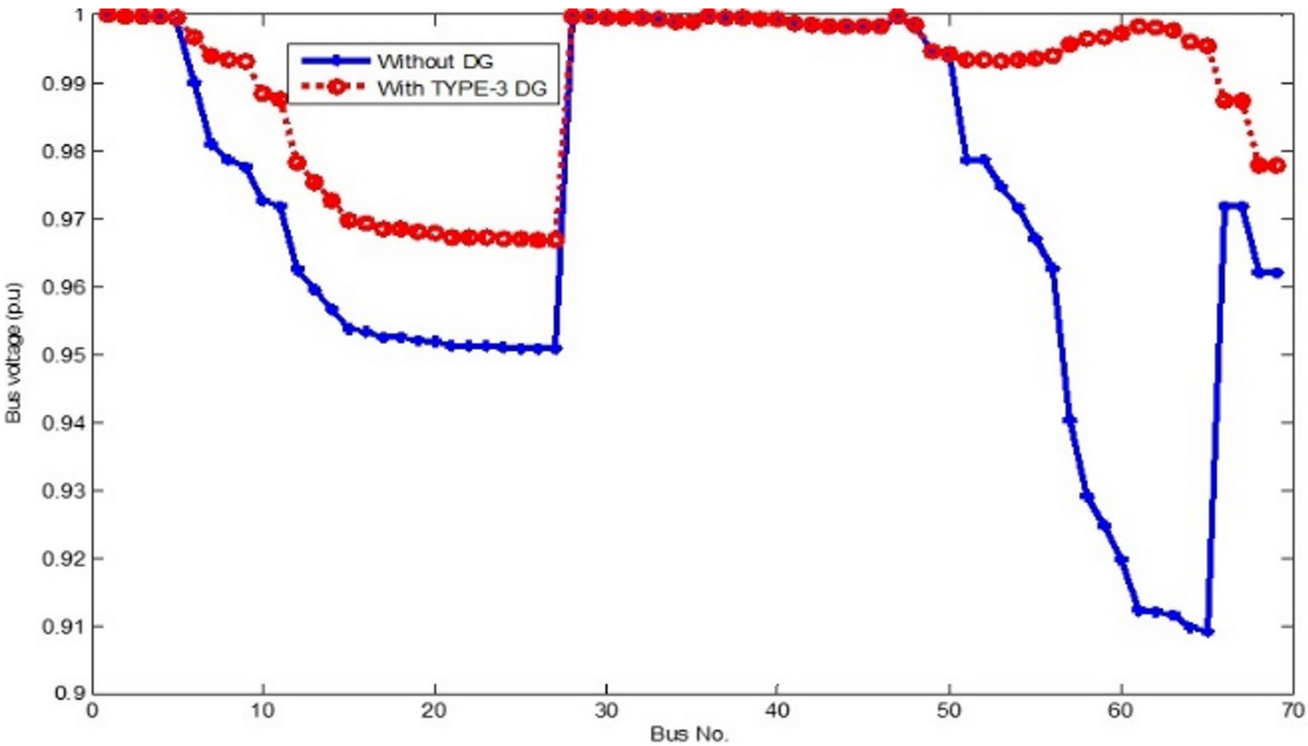

Fig. 13 At each bus variation in voltage

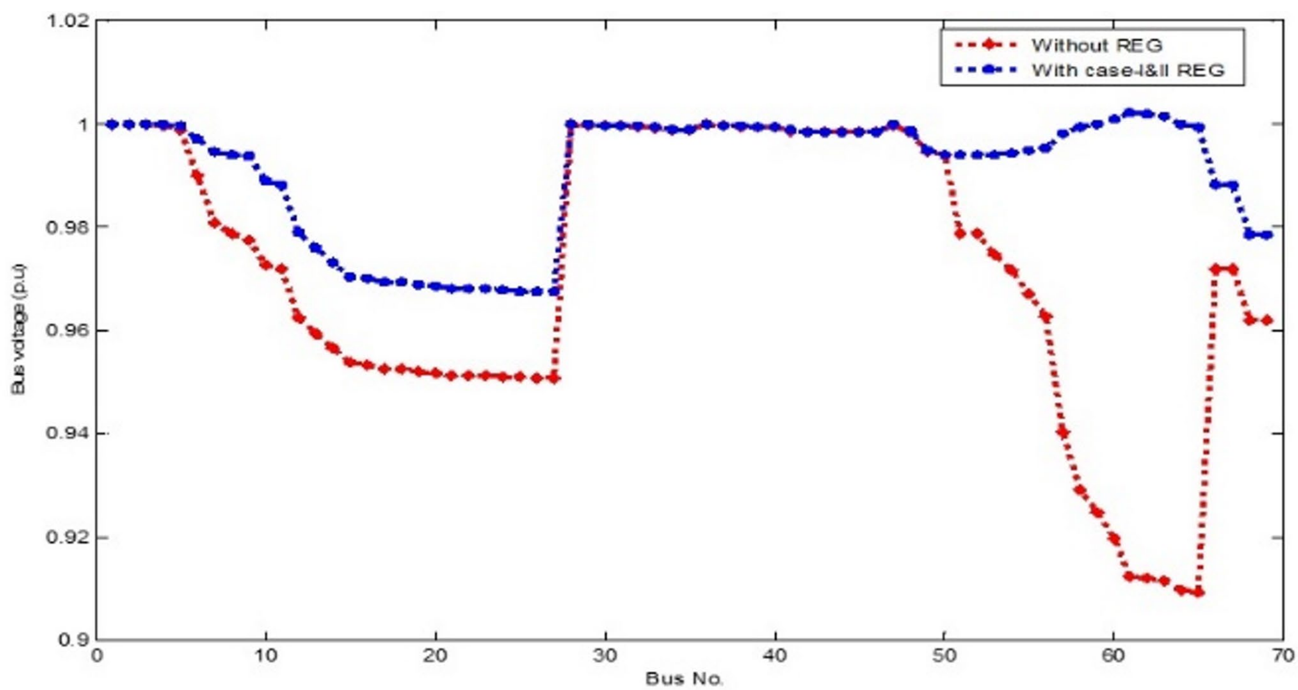

Fig. 14 At each bus combines for case-IV for variation in voltage

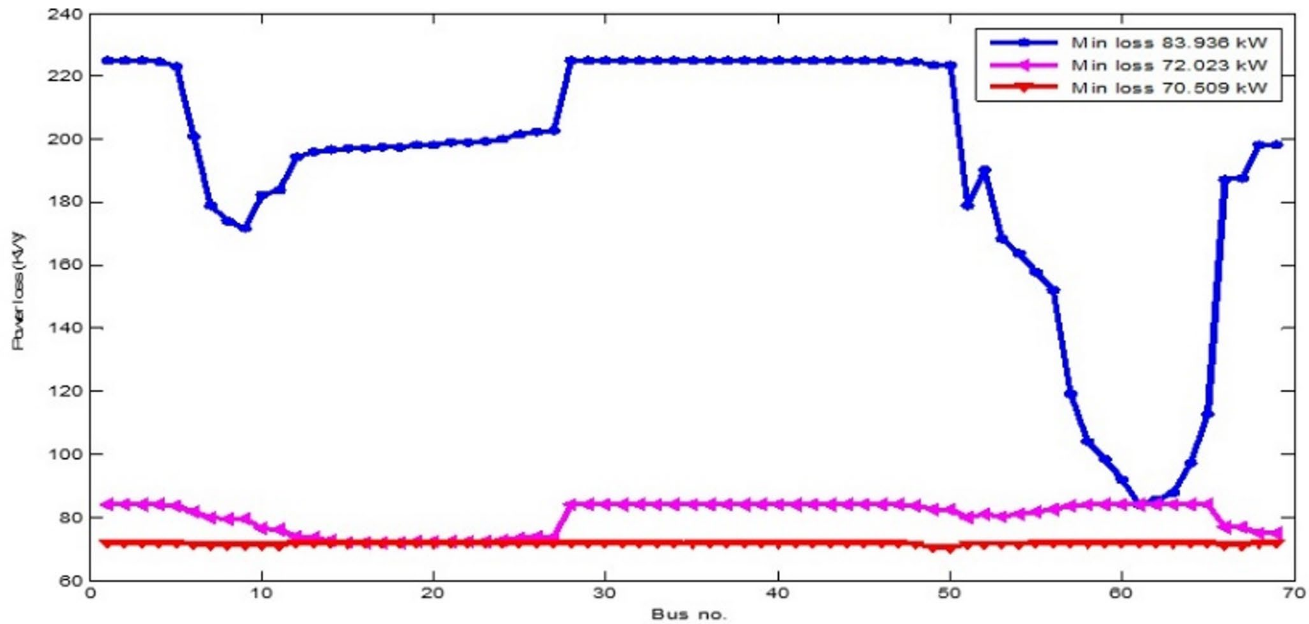

Fig. 15 The loss at each bus

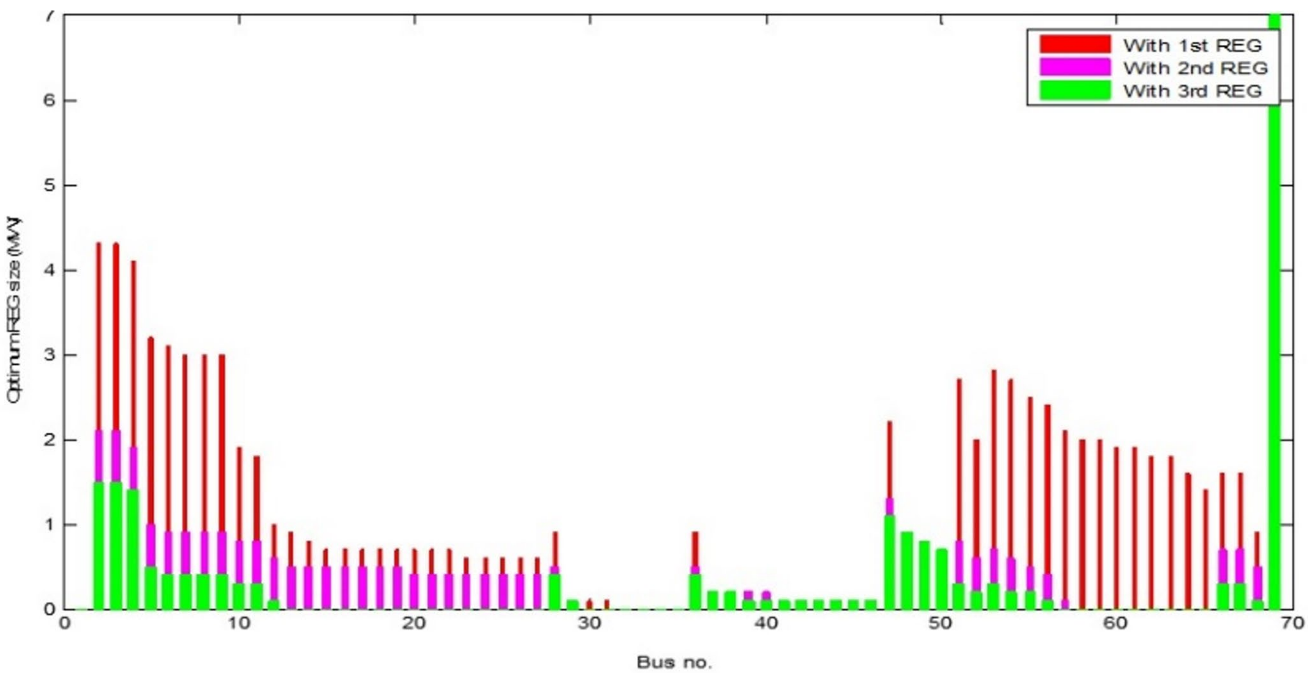

Fig. 16 The size at each bus

4.2 The 118-bus Radial Distribution System

The proposed algorithm is evaluated on a 118-bus radial distribution network, depicted in Fig. 18, which has 118 buses, 117 branches, a 12.66 kV nominal voltage, and 15 tie switches. The total demandis 22,709.7 kW and 17,041.1 kVAR. Without distributed generation (DG), the real and reactive power losses were 4140 kW and 3254.2 kVAR, respectively, with a minimum voltage of 0.64154 pu.

4.2.1 Case-I: Injecting Real Power

Without REG, losses were 4140 kW and 3254.2 kVAR, with a minimum voltage of 0.64154 pu. When REG were installed, the total real power loss decreased to 2321 kW,

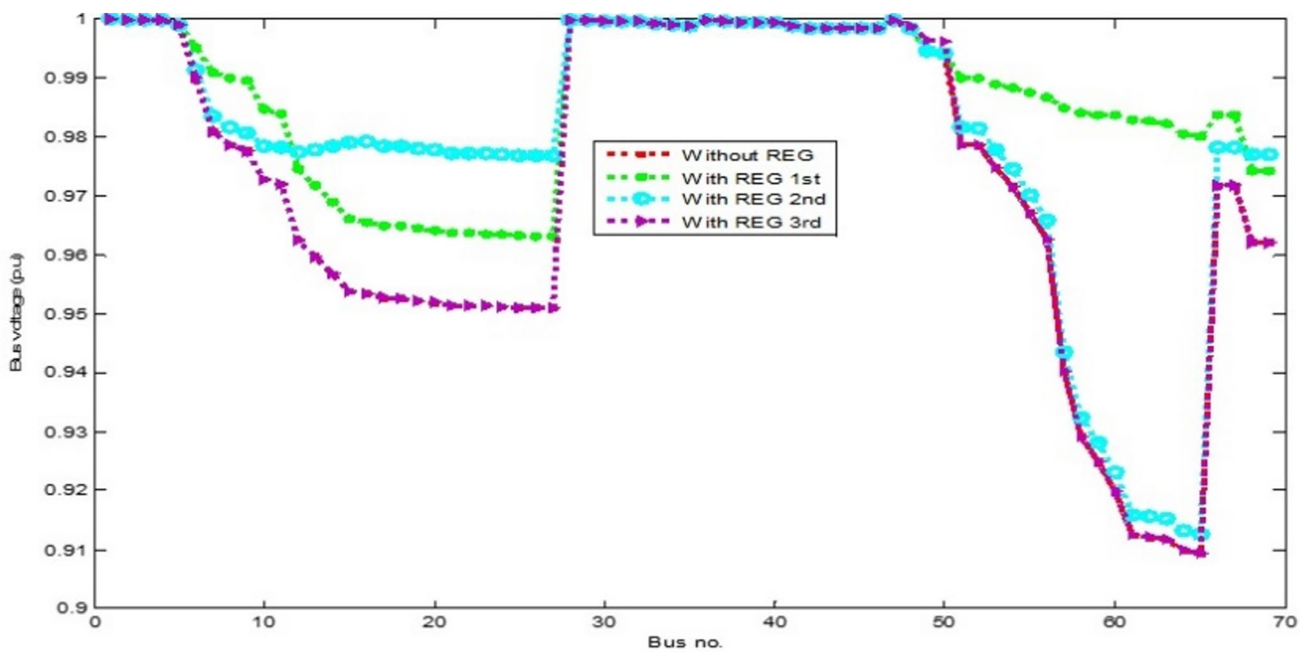

Fig. 17 At each bus for voltage Variation

Table 2 A comprehensive comparison for case-I to case-V (69 bus system)

Parameters	Case						
	Base Case	I	II	III	IV	V	
Power losses (KW)	225	83.936	152.43	24.217	24.346	72.023	70.509
Bus Location	---	61	61	61	61	61, 16	61,16,50
Loss Reduction (%)	---	62.70	32.25	89.24	89.18	67.99	68.66
Vmin	0.90942	0.96318	0.9305	0.96695	0.96764	0.91271	0.90943
Voltage profile (%)	---	5.58	2.26	5.94	6.01	0.36	0.01
REG Size	---	1.9 MW	1.3 MVAr	2.2 MVA	1.3 MVAr	1.9 & 0.5 (MW)	1.9, 0.5 & 0.7 (MW)

Table 3 A comparative analysis for REG size/location

Algorithms / Technique	Invasive weed optimization [37]	Bacterial Foraging Optimization Algorithm [39]	Loss sensitivity Factor Simulated Annealing [40]	Genetic algorithm [38]	Particle swarm optimization [38]	Harmony Search Algorithm [36]	Proposed Method
Power loss (kW)	74.59	75.23	77.1	89.0	83.2	86.77	70.509
Minimum voltage (bus)	0.9802	0.9808	0.9811	0.9936	0.9901	0.9677	0.90943
% loss reduction	66.79	66.56	65.73	60.44	63.02	61.43	68.66
REG size (MW) /Location	0.12381(27), 0.4334 (65), & 1.3266(61)	0.2954 (27), 0.4476(65), & 1.3451 (61)	0.4204 (18), 1.3311(60), & 0.4298 (65)	0.9297 (21), 1.0752 (62), & 0.9925(64)	1.1998 (61), 0.7956 (63), & 0.9925(17)	0.1018(65), 0.3690(64), & 1.3024(63)	1.9 (61), 0.5(16), & 0.7(50)

and the optimal size of the REG becomes 5.3 MW at bus 95 (shown in Figs. 19 and 20). The minimum voltage profile improved to 0.68834 p.u. as determined using the RLF method. The improvement in voltage profile compared to without REG located is depicted in Fig. 21.

4.2.2 Case-II: Injecting Reactive Power

In the base case without REG, the total real and reactive power losses were calculated to be 4140 kW and 3254.2 kVAR, respectively. When a REG was installed at bus 64 in Case II, the optimal real power loss becomes 3254.2 kW. The optimal size for this REG was determined to be 4.6 MVAr, as shown in Figs. 22 and 23. The minimum voltage

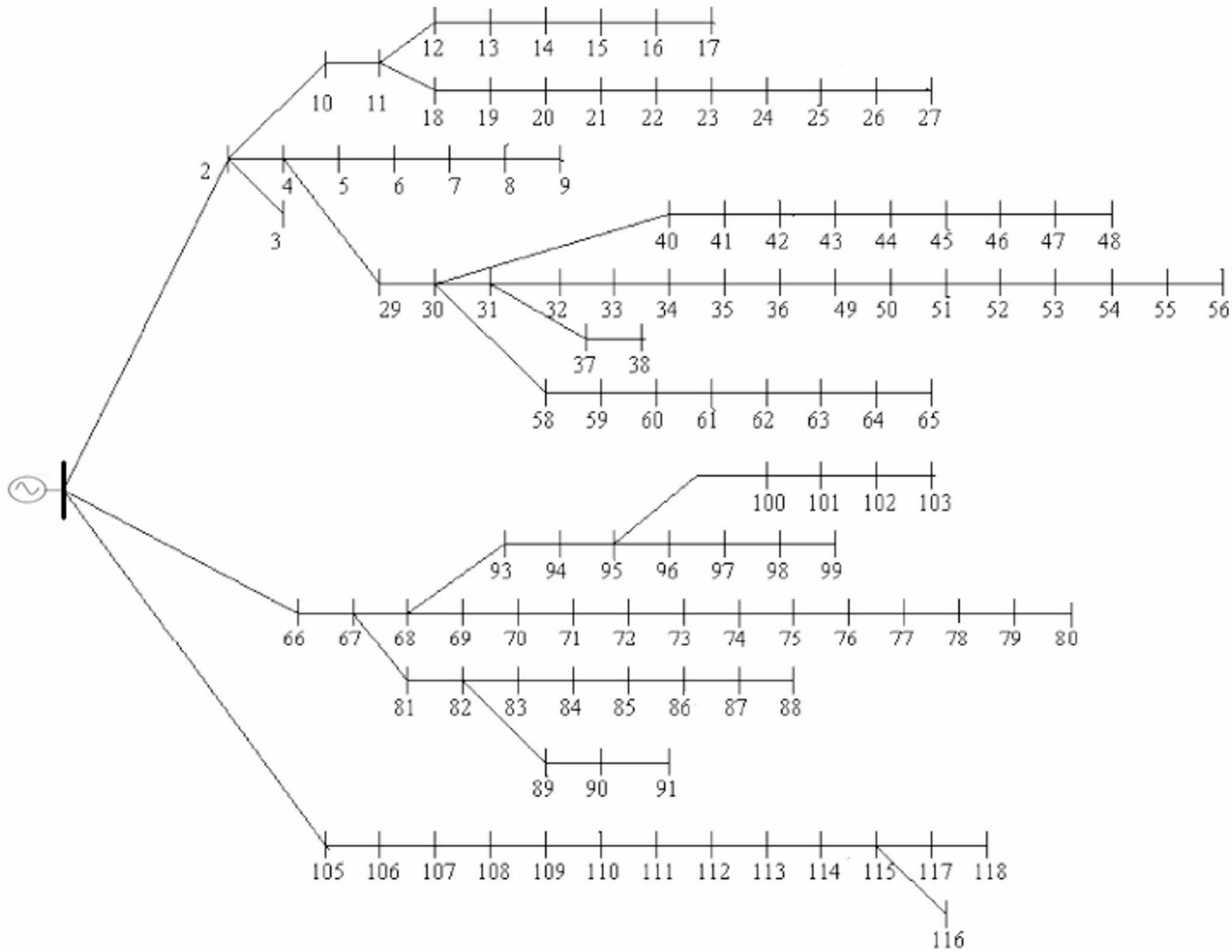

Fig. 18 A 118 bus radial distribution network

profile of 0.69279 pu was observed at bus 38.The variation voltage profile improvements as compared to base case represented in Fig. 24.

4.2.3 Case-III: Injecting Real and Reactive Power for All Power Factors

Six different power factors were considered: 0, 0.5, 0.8, 0.82, 0.9, and 1.0. The power loss associated with each power factor is illustrated in Fig. 25.For the corresponding power factors, the optimal power losses were found to be 3254.2 kW, 2164.1 kW, 1805.1 kW, 1799.5 kW, 1823.4 kW, and 2321 kW, respectively. Additionally, the optimal REG size was determined to be 4.6 MW, 5.5 MW, 6.0 MW, 6.0 MW, 6.0 MW, and 5.3 MW, respectively, with the preliminary optimal location consistently at bus 95, as shown in Figs. 26 and 27. Among the six buses, bus 95 was identified as the optimal location for the REG, with a minimum loss of 1799.5 kW and an optimal size of 6.0 MVAr at a power factor of 0.82. The voltage profile improvement achieved with the REG is shown in Fig. 28. The minimum voltage profile was observed to be 0.68834 pu.

4.2.4 Case-IV: Injecting Real and Reactive Power Associated With Case-I & Case-II

The enhanced voltage profile achieved with the use of REG is illustrated in Fig. 29. This improvement is superior to the results obtained in individual Case I and Case II.

4.2.5 Case-V: Injecting Real Power Multi REG

For the three REG, the optimal locations were determined to be buses 95, 50, and 48. The corresponding minimum losses were 2321 kW, 1734.2 kW, and 1507 kW, respectively. The optimal REG sizes for these locations were 5.3 MW, 6.2 MW, and 2.4 MW, as shown in Figs. 30 and 31.

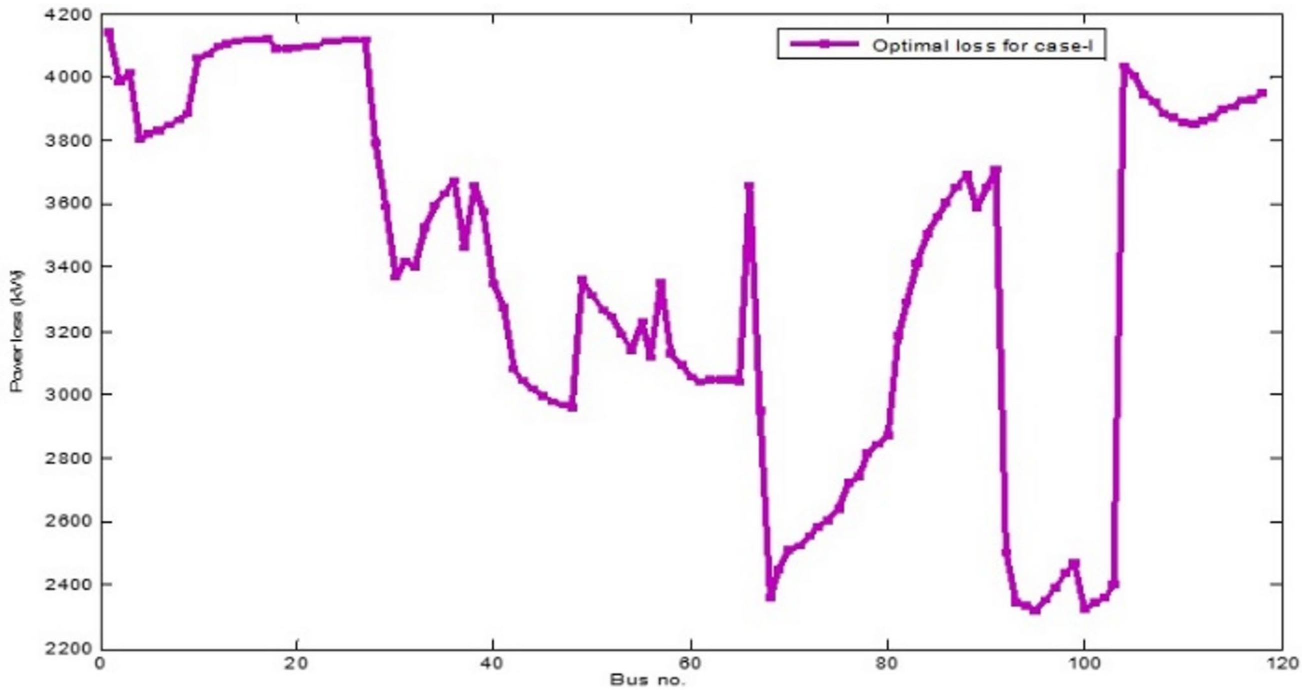

Fig. 19 The losses at each bus

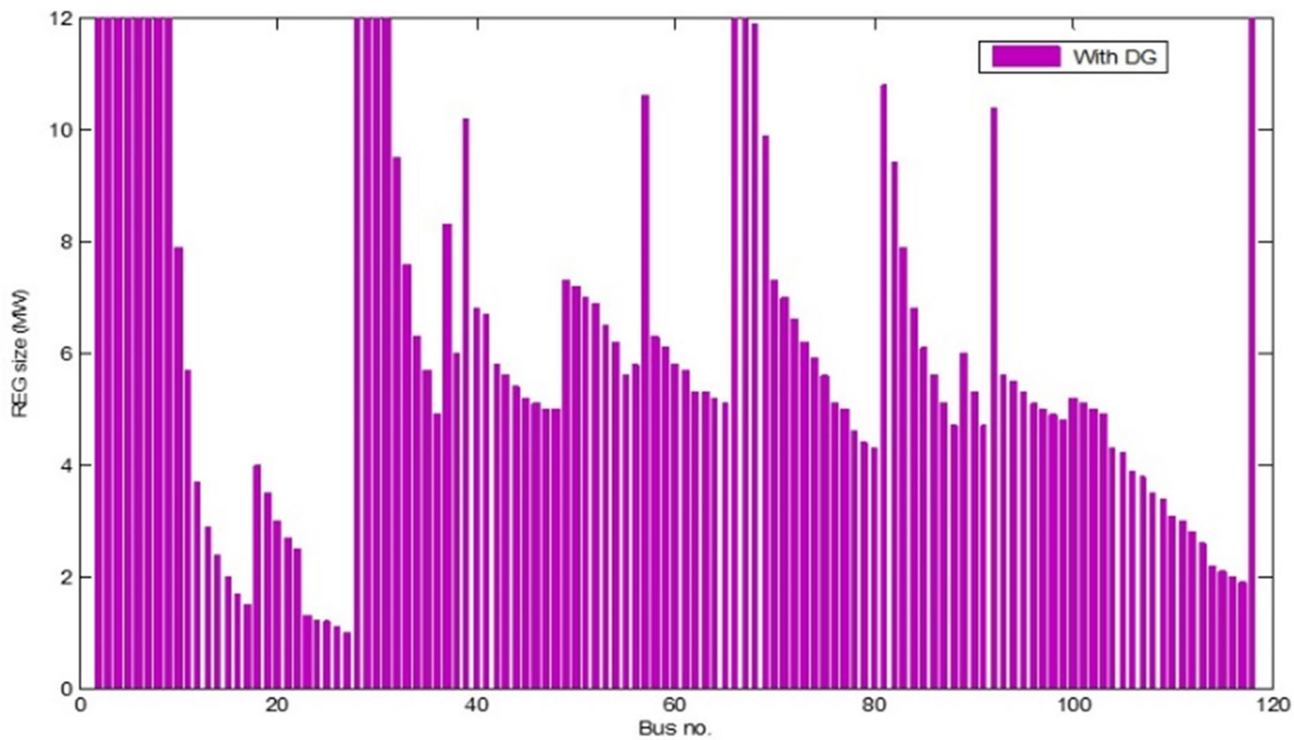

Fig. 20 The size at each bus

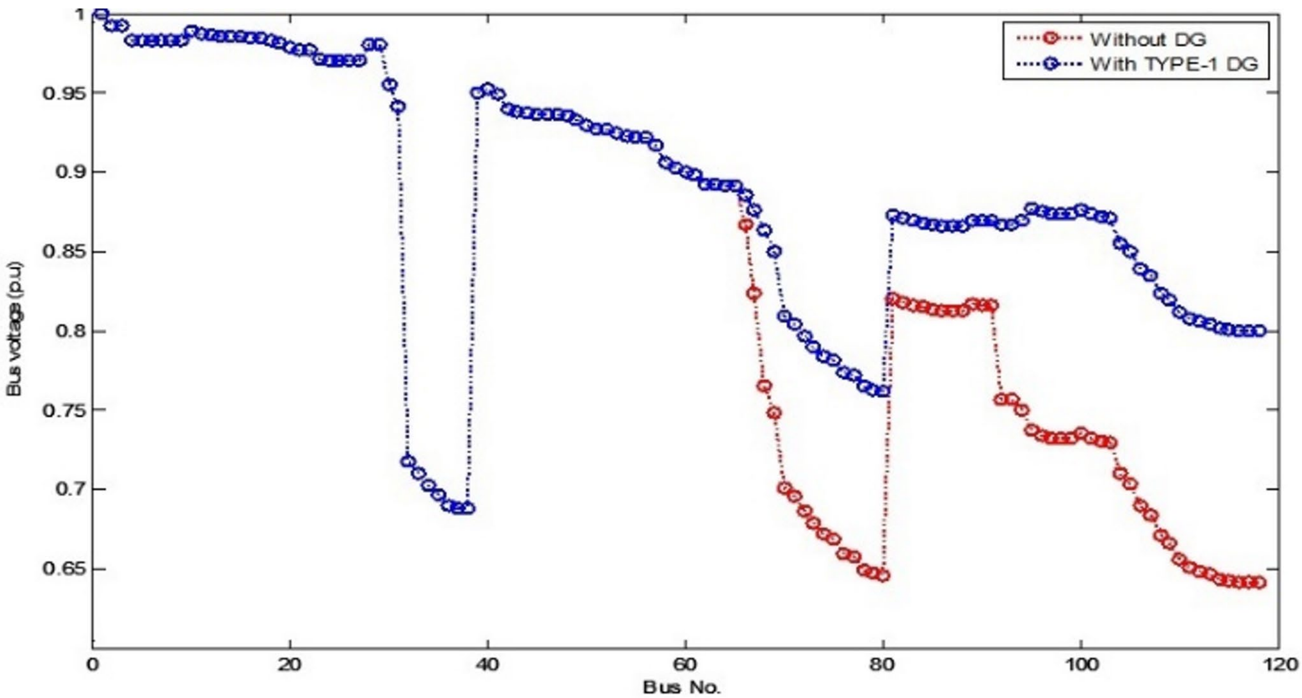

Fig. 21 The voltage profile with and without REG at each bus

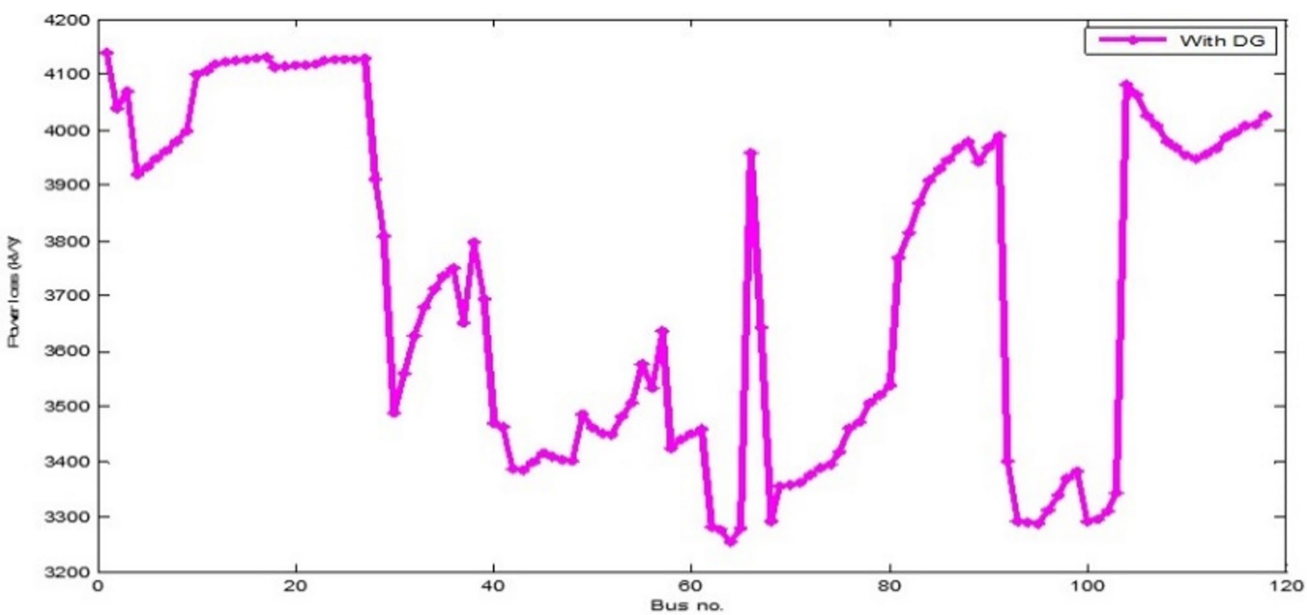

Fig. 22 Optimal loss with REG at each bus for118-bus system

Additionally, when combining the first and second REG at buses 95 and 50, the optimal sizes were determined to be 5.3 MW and 6.2 MW, respectively. This combination resulted in a power loss of 1734.2 kW and a voltage profile improvement of 0.68538 p.u. Furthermore, placing all three REG at buses 95, 50, and 48 jointly yielded optimal sizes of 5.3 MW, 6.2 MW, and 2.4 MW, respectively. The corresponding voltage profile improvements were 0.68834, 0.68538, and 0.70227 p.u. as shown in Fig. 32.For this configuration, the combined power loss was 1507 kW, and the voltage profile improvement was 0.70227 p.u. Table 4 summarizes the results for Cases I to V.

Among Cases I to V, Case V, which utilizes three REG, achieved the highest loss reduction of 63.60% and the greatest voltage profile improvement of 8.65%. Case III also performed well, with a minimum loss of 56.53% and a voltage

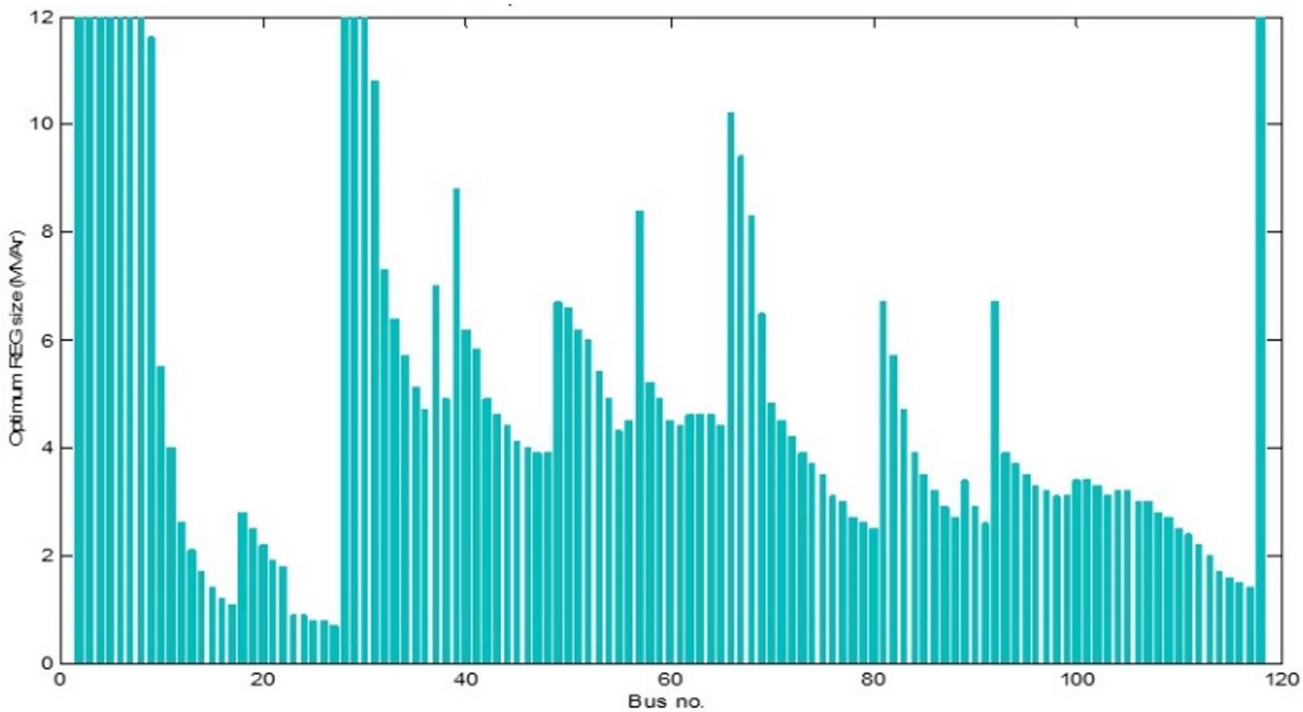

Fig. 23 The size at each bus

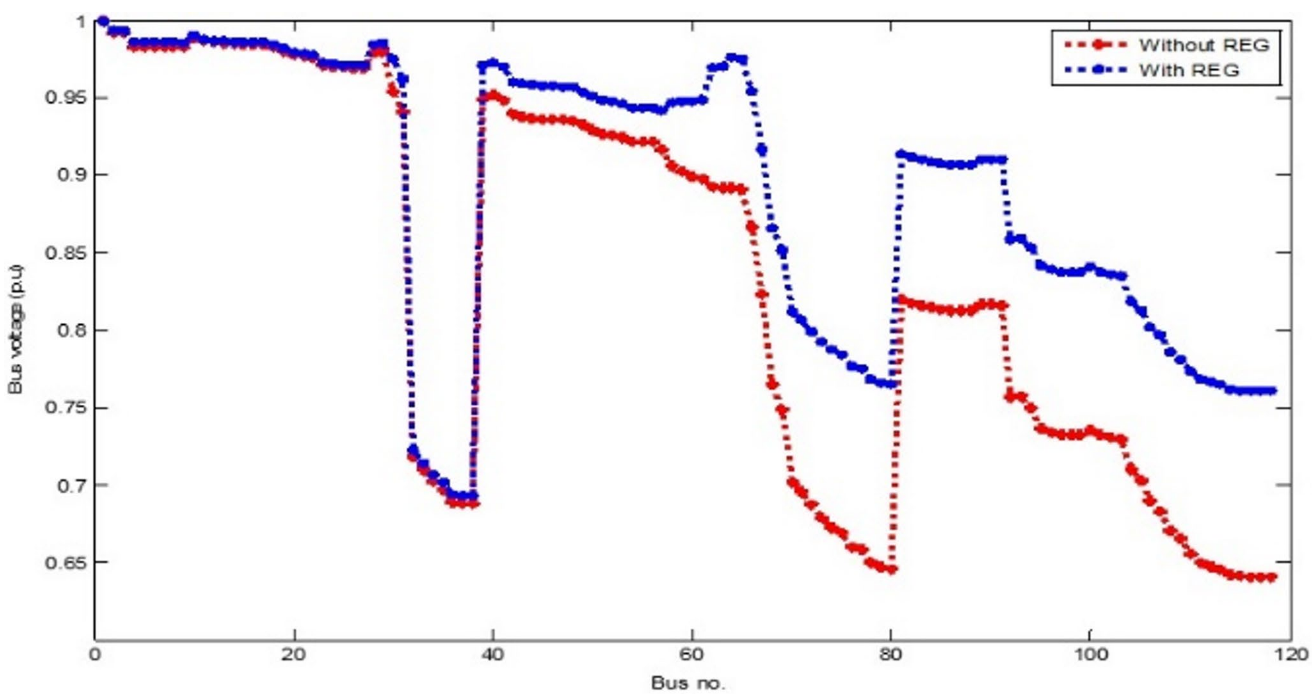

Fig. 24 The voltage profile Variation with and without REG at each bus

profile improvement of 6.80%. The other cases, IV, I, and II, had loss reductions of 52.40%, 43.94%, and 21.40%, respectively, and voltage profile improvements of 7.40%, 6.80%, and 7.40%, respectively. Clearly, Cases V and III demonstrate the most significant benefits of REG installation, offering both substantial loss reduction and notable voltage profile improvements. Therefore, the combined bus location at 95 is the most suitable placement for REG in the 118-bus test distribution network. Table 4 compares the proposed RLF approach with other techniques. The RLF approach

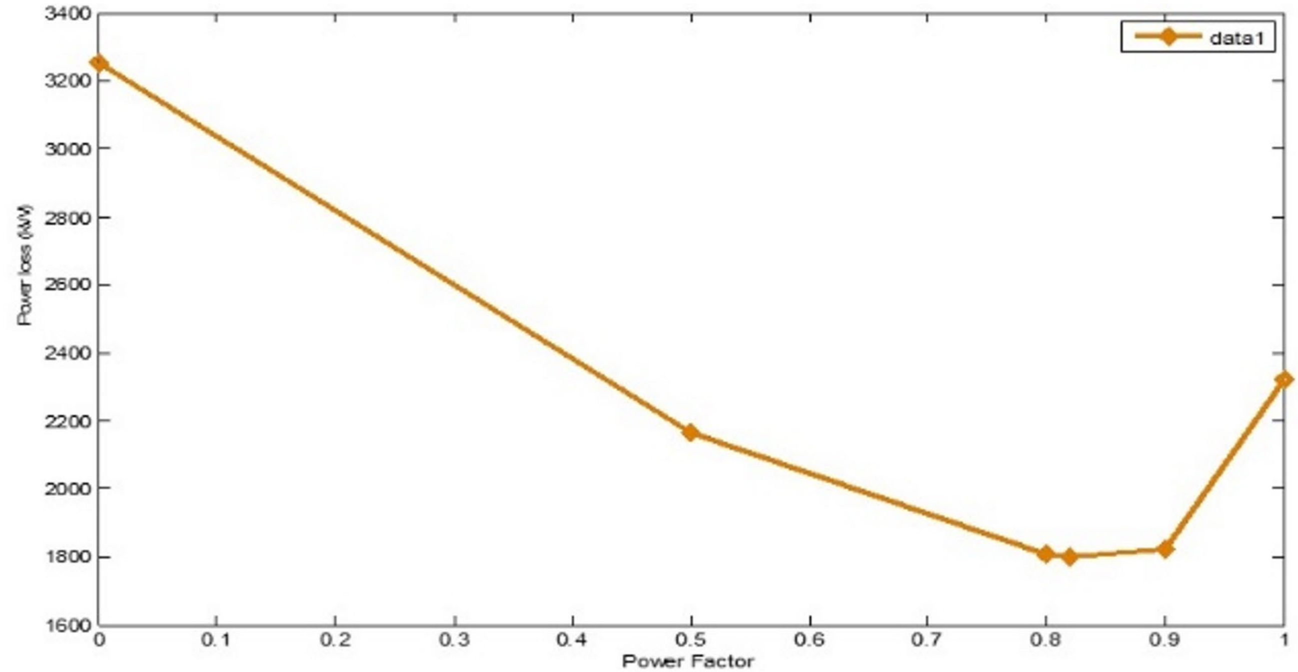

Fig. 25 The real power losses at all used power factor

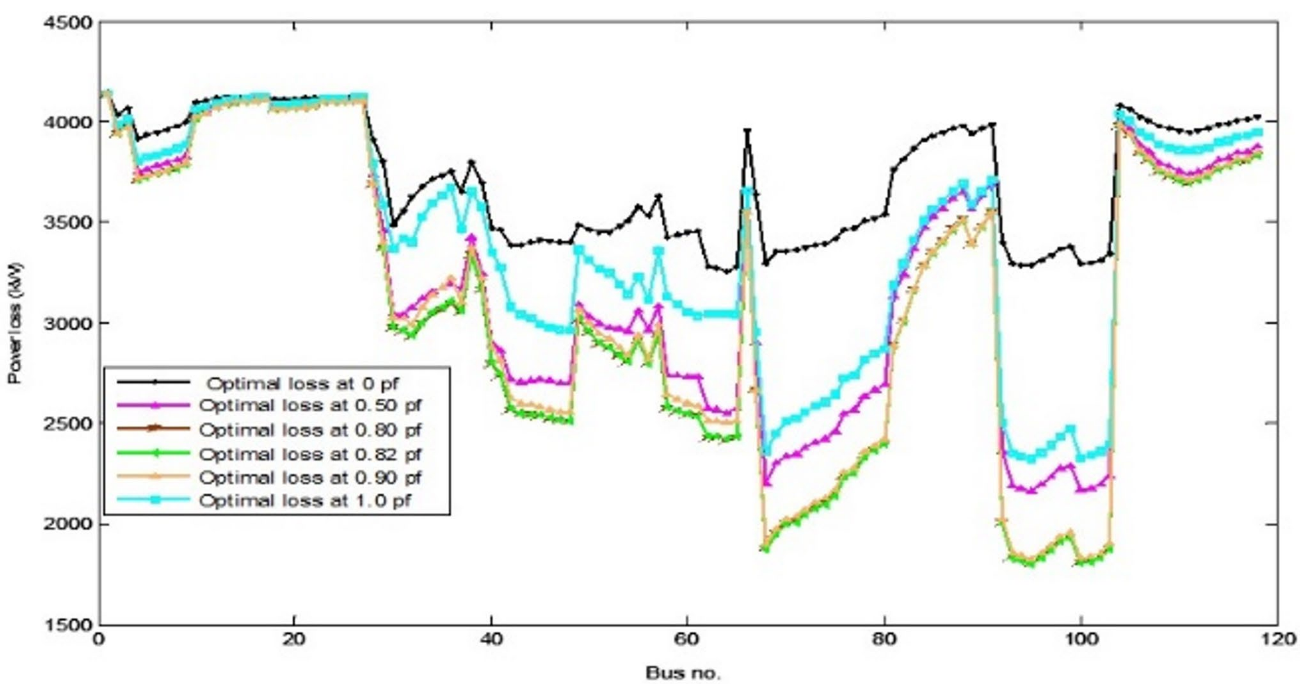

Fig. 26 The loss of power at each bus

achieved a loss reduction of 63.60%. This indicates that the proposed approach is an effective and efficient solution for REG placement and sizing in power distribution systems.

Among Cases I to V, Case V, which utilizes three REG, achieved the highest loss reduction of 63.60% and the greatest voltage profile improvement of 8.65%. Case III also performed well, with a minimum loss of 56.53% and a voltage profile improvement of 6.80%. The other cases, IV, I, and II, had loss reductions of 52.40%, 43.94%, and 21.40%, respectively, and voltage profile improvements of 7.40%, 6.80%, and 7.40%, respectively. Clearly, Cases V and III demonstrate the most significant benefits of REG installation,

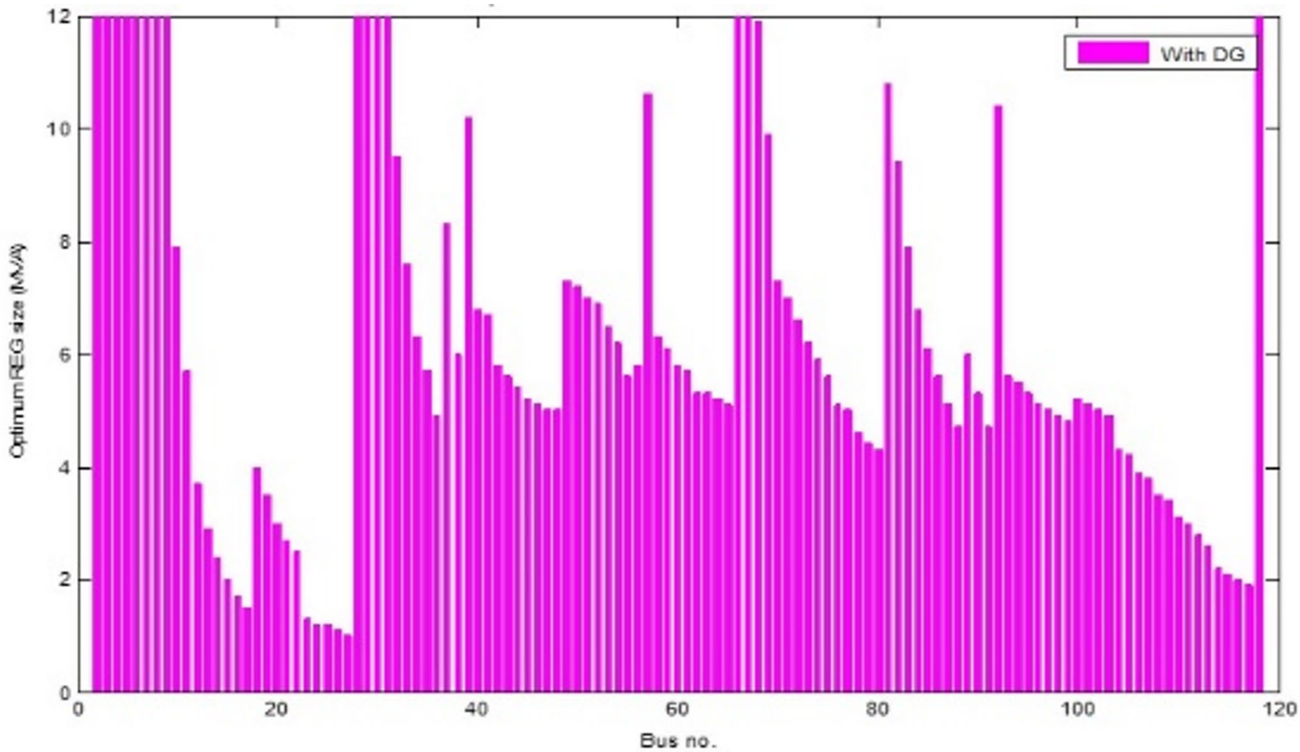

Fig. 27 The size at each bus

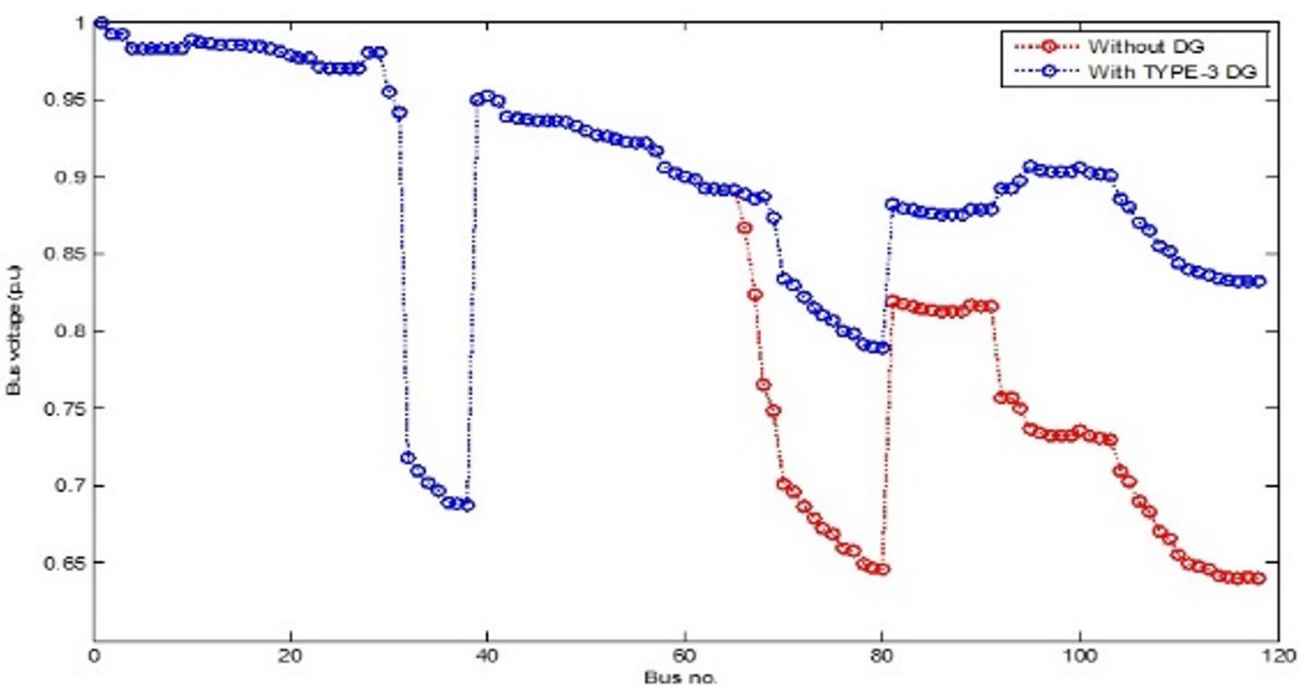

Fig. 28 At each bus for Variation in voltage

offering both substantial loss reduction and notable voltage profile improvements. Therefore, the combined bus location at 95 is the most suitable placement for REG in the 118-bus test distribution network. Table 5 compares the proposed RLF approach with other techniques. The RLF approach achieved a loss reduction of 63.60%. This indicates that the proposed approach is an effective and efficient solution for REG placement and sizing in power distribution systems.

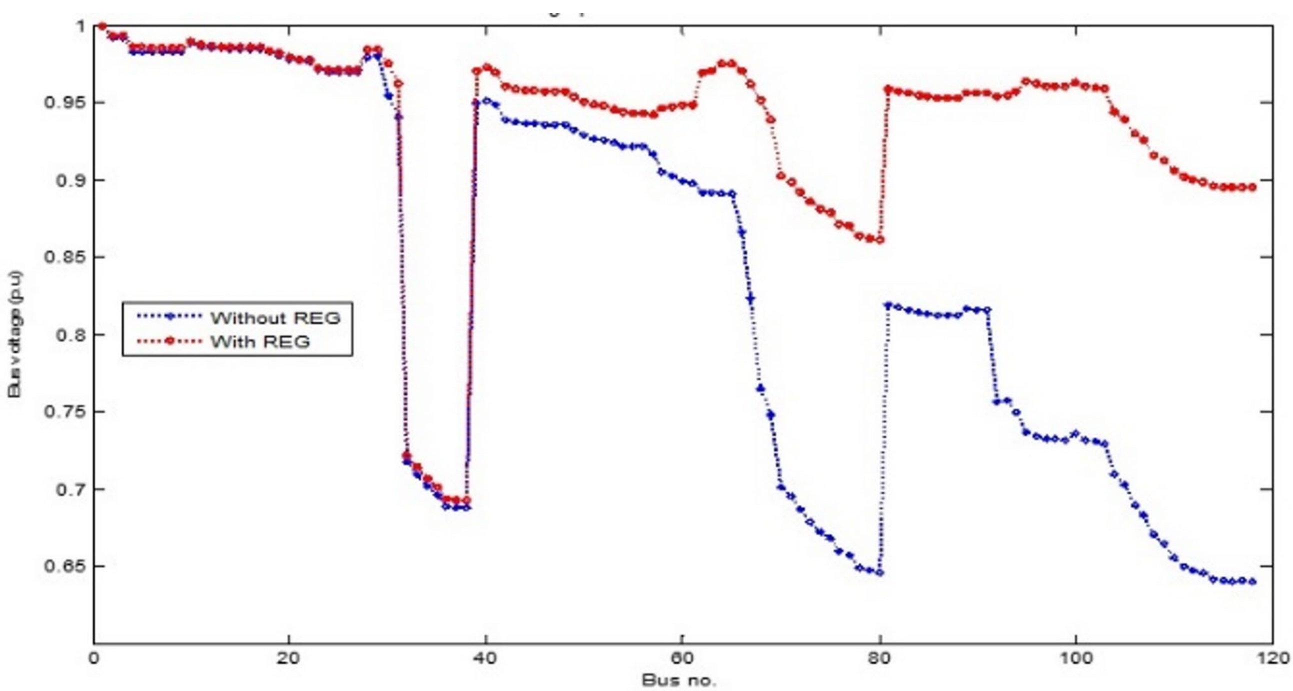

Fig. 29 At each bus combines for voltage Variation

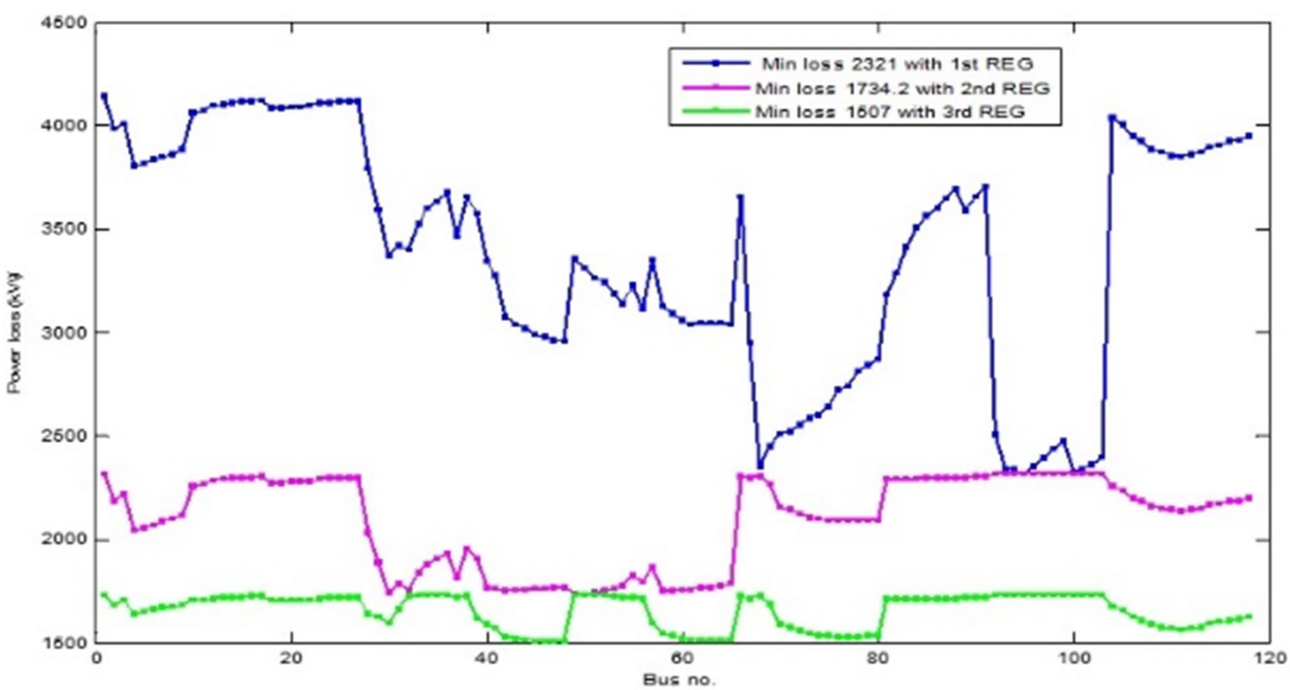

Fig. 30 The loss at each bus with multi-REG

5 Conclusion

This paper presents an optimal bus location algorithm REG using the RLF technique in 69-bus and 118-bus networks. The basic technique was explained using a smaller 33-bus distribution system. This approach effectively determines bus locations and REG sizes within distribution systems while considering parametric constraints. The proposed method not only minimizes line losses but also effectively regulates REG sizes to maintain acceptable voltage levels

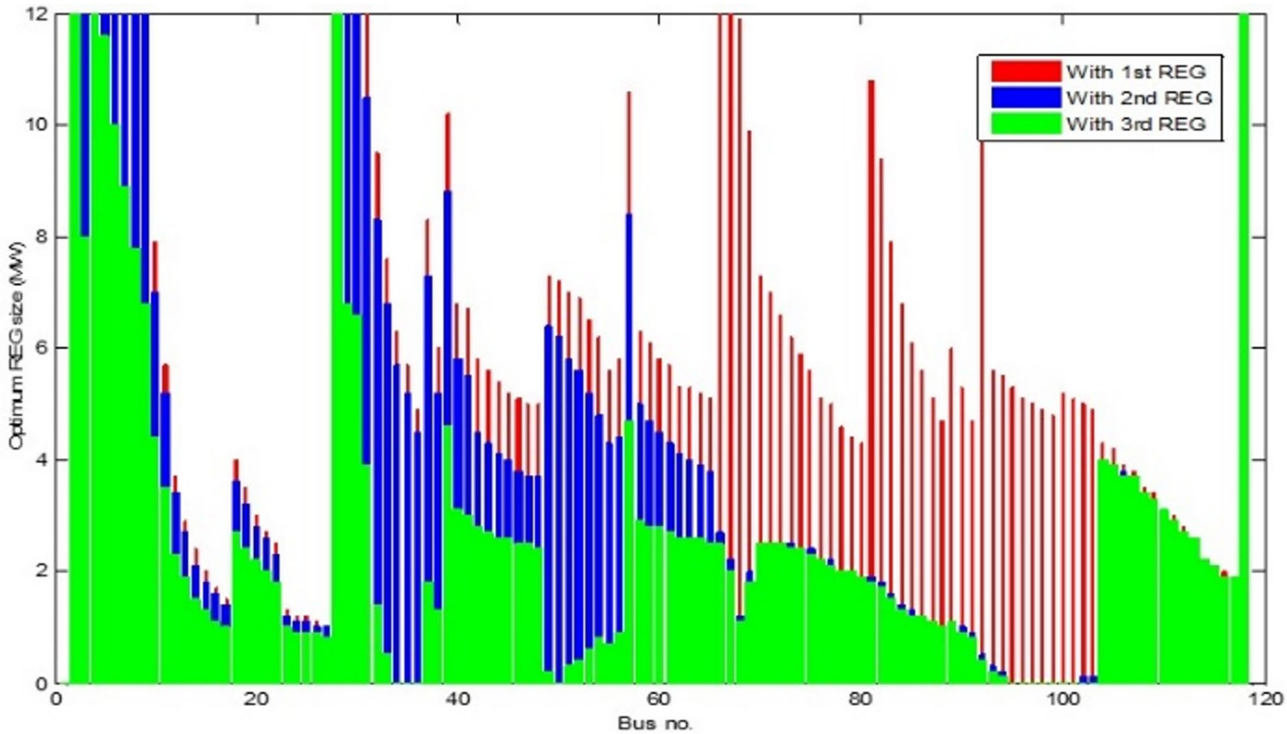

Fig. 31 The size at each bus

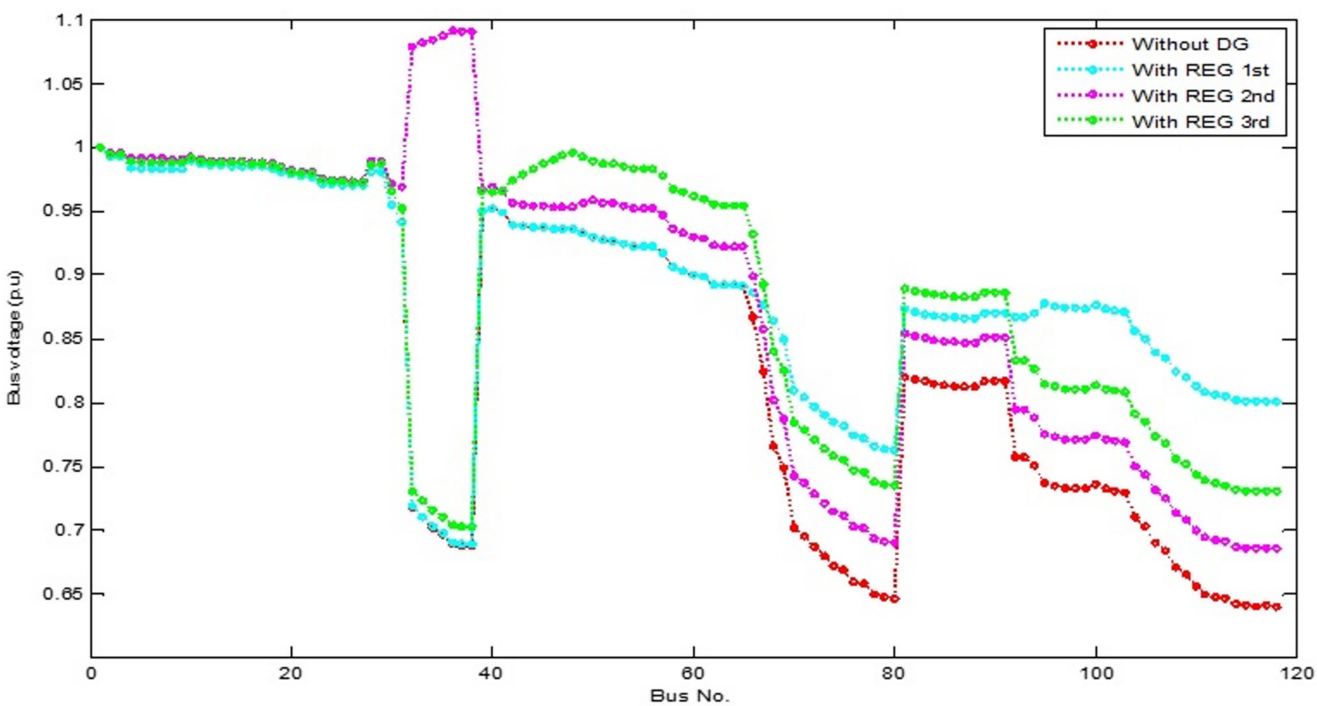

Fig. 32 At each bus voltage variation profile with multi REG

Table 4 A comprehensive comparison for case-I to case-V (118 bus system)

Parameters	Case						
	Base Case	I	II	III	IV	V	
Power losses (KW)	4140	2321	3254.2	1799.5	1970.5	1734.2	1507
Bus Location	--	95	64	95	95/64	95/50	95/50/40
Loss Reduction (%)	--	43.94	21.40	56.53	52.40	58.11	63.60
Vmin	0.64154	0.68834	0.69279	0.68834	0.69279	0.68538	0.70227
Voltage profile (%)	--	6.80	7.40	6.80	7.40	6.40	8.65
REG Size	--	5.3 *(MW)*	4.6 *(MVAr)*	*6 (MVA) with PF 0.82*	5.3 MW/4.6 *(MVAr)*	5.3 & 6.2 *(MW)*	5.3, 6.2 & 2.4 *(MW)*

Table 5 A comprehensive comparison for case-I to case-V according to technique for optimal locations

Parameters	Method/Technique								
	Loss sensitivity Factor LSF(kW)			HYBRID (kW)			Proposed RLF Method (kW)		
Parameters in Case I for single REG									
REG location	70			71			95		
REG Size	3050			3000			5.3		
Base Case Loss	1298			1298			4140		
Power Loss (kW)	1021			1016			2321		
% Loss	21.33			21.67			43.94		
Parameters in Case V for three REG									
REG location	70	30	64	71	47	108	95	50	40
REG Size	2800	6800	4700	2950	3250	3200	5.3	6.2	2.4
Base Case Loss	1298.1 kW			1298.1 kW			4140 kW		
Power Loss (kW)	904.38			677.74			1507		
% Loss	30.33			47.78			63.60		

within the distribution system. Furthermore, the method determines the optimal power factor to further reduce power losses. Simulation results demonstrate that REG capable of injecting both real and reactive power at different power factors (Case III REG) are best suited for enhancing voltage profiles at all buses, although they may have slightly higher losses compared to Case IV REG. Conversely, Case IV REG, which can inject both real and reactive power, are ideal for reducing power losses, even if they may have slightly lower voltage profile improvements compared to Case III. Ultimately, buses 61 and 95 were identified as the most suitable locations for REG in the 69-bus and 118-bus networks, respectively. The benefits of minimizing power loss include reduced stress on feeder loading, decreased power flow in feeder lines, increased equipment lifespan, and the ability to accommodate increased load demand. These improvements ultimately lead to reduced customer bills.

This study mainly purposes to minimize power losses and improve voltage profiles within distribution networks to enhance overall network efficiency. Although economic factors, such as deployment costs, are vital in practical applications, they were not included in this research for several reasons. First, the main goal was to demonstrate the technical effectiveness of the proposed optimization approach, which considers active power, reactive power, combined real and reactive power, and optimal power factor all of which play a key role in minimizing system losses in a distribution network, as achieved through the RLF Technique. Second, cost considerations can vary significantly depending on factors such as location, energy policies, and regional economic conditions, making it difficult to generalize financial outcomes. Finally, future work will build upon this study by incorporating economic constraints and investment considerations into the REG placement model for cost-based optimization.

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Data Availability The data sources employed for analysis are presented in the text.

Declarations

Conflict of Interest The authors declare that there is no conflict of interest.

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