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Optimization of Voltage Profile and Power Loss Reduction in Iraqi Distribution Networks under High Load Conditions with Renewable Energy Integration

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Abstract: Electrical distribution networks in developing countries, including Iraq, suffer from significant power losses and voltage instability, especially under high-load conditions during peak summer demand. Conventional approaches such as capacitor placement, distributed generation (DG), and network reconfiguration have been widely applied; however, these methods are typically implemented independently and often fail to provide sufficient performance improvement under realistic operating conditions.To overcome these limitations, this study proposes a hybrid optimization framework that integrates solar photovoltaic (PV) generation, optimal capacitor placement, and network reconfiguration within a unified model. A modified IEEE 33-bus system is used to simulate Iraqi network conditions with a 40% load increase. The optimization problem is formulated as a multi-objective function and solved using Particle Swarm Optimization (PSO).The results demonstrate that PV integration alone reduces power losses by approximately 24%, while the proposed hybrid approach achieves up to 42% reduction. Furthermore, the minimum bus voltage is improved from 0.88 pu to 0.975 pu, ensuring compliance with standard operational limits.These findings demonstrate that the proposed approach provides a more effective and practical solution for improving the performance and reliability of distribution networks under high-load conditions.

Keywords: Hybrid Optimization, Power Loss Reduction, Voltage Profile Improvement, Particle Swarm Optimization (PSO), High-Load Conditions

1. Introduction

Operational challenges in electrical distribution networks in developing countries, such as Iraq, are becoming major problems, as the number of loads grows rapidly, the infrastructure ages, and modernization of the system is not carried out. These issues are especially problematic in the extreme climatic conditions when the peak electricity demand grows significantly during the summer seasons and tends to go beyond the capacity of a system, resulting into poor performance and lower reliability[1], [2] .Combination of distributed generation (DG) and especially solar photovoltaic (PV) systems has taken place in the recent years as an efficient strategy in enhancing voltage profiles and minimizing power losses in distribution systems[3] [4] . The solar energy potential of the country is relatively high because solar irradiance levels are observed to be very high all year round; hence, PV integration is a potential and attractive option for Iraq . Nevertheless, poor or inadequate integration of PV systems can also bring about technical issues like the change in voltage and reverse power flow that has an adverse impact on system [5].Some of the optimization methods that have been presented to reduce these problems over the years are optimal capacitor placement, distributed generation, and network reconfiguration. Although these methods have been shown to improve when used independently, they have not been sufficiently studied as a system under high-load conditions.[6]In order to eliminate these constraints, this paper suggests a hybrid optimization model, which incorporates the solar PV generation, capacity location, and network reconfiguration into a single model. The proposed solution will reduce losses to power and enhance voltage profiles under high-load conditions and will offer a more realistic and effective solution to the improvement of performance and reliability of distribution networks [7] .

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In contrast to the earlier works which would independently optimize the methods of generating power as well as the allocation of capacitor, the current paper suggests a synchronized hybrid approach which also optimizes the placement of the distributed generation, capacitor identification, and the network structure under peak load situation. This is a tremendous move towards solving real life operation problems in formulating the power systems[8].

2. Literature Overview

In the recent decade, much research has been done on the optimization of the performance of electrical distribution networks through different optimization methods. These include, but are not limited to, optimal capacitor placement which has been generally adopted as a viable strategy of minimizing power loss due to reactive capacitors and also improving voltage profiles. It has been established that proper assignment of capacitor banks could greatly enhance voltage stability as well as minimise system losses particularly in the radial distribution systems [9], [10]. The method however is mainly to cover the reactive power compensation but not sufficiently to take into consideration the active power optimization under fluctuating load conditions.Meanwhile, the deployment of distributed generation (DG) and solar photovoltaic (PV) systems in particular have received significant interest owing to the benefits of environmental and operational footprint. It has been demonstrated in the past that effective location and size of DG units may be used to ensure that line losses are minimized, the voltage regulation is improved, and the overall efficiency of the system is enhanced . However, high penetration rates of PV can pose operational difficulties like voltage increase and reverse flow of power, which can pose some adverse effects on the stability of the system when they are not managed [11], [12].The other established method that has been applied to reduce power losses and load distribution in radial networks is network reconfiguration. The flow of power can be optimally modified by changing the state of the switches, which leads to the better performance of the system under various loading conditions [13]. Although it is quite effective, this approach could be insufficient to deliver adequate improvement in cases where the conditions of loading the system change considerably.Though these techniques have shown good outcomes separately, the majority of the literature available is devoted to the individual optimization strategies, but not integrated . In addition, most of such studies are done when loading in normal conditions, which are not necessarily the real conditions in the developing world where high-load conditions are prevalent like in Iraq[14] . In order to overcome these shortcomings, this research suggests a hybrid optimization model that would combine solar PV generation, capacitor placement and network reconfiguration in case of high load conditions. This is a coordinated solution to attempt to offer a more holistic and efficient solution to improving voltage profile and minimizing power losses within the distribution networks (2225,27). System Modeling [15], [16]

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2.1 Network Model

The electrical distribution system considered in this study is based on the standard IEEE 33-bus radial distribution network, which is widely used as a benchmark system for evaluatingload flow analysis, power loss minimization, and voltage stability in distribution networks.The system is 12.66 kV with the total load demand of 3.72 MW and 2.3 MVAr. The network is distinguished by the radial topology, and the ratio of resistance-to-reactance (R/X) is high and thus it is useful in modeling realistic distribution systems, especially in developing countries.In order to model real operating conditions in the distribution networks of Iraq, the load demand at all buses is increased by 40 percent. This adjustment reflects peak loading conditions which is normally evident in extreme summer season when the demand of power is high and far above the normal operating load.The choice of the IEEE 33-bus system offers a unified platform where performance analysis can be performed and allows a direct comparison with the already published research.

2.1.1 Transformer Losses

Transformer losses were not explicitly modeled in the original formulation because the primary focus of this study was on feeder power loss reduction under high-load conditions. However, transformer copper and core losses represent an important component of technical losses in practical distribution systems,

particularly in aging infrastructures such as Iraqi networks. Therefore, transformer losses are acknowledged as an additional operational factor that can influence the total system efficiency. Future work may incorporate detailed transformer models into the optimization framework for more comprehensive analysis.[17][18].

2.2 Load Modeling

All loads in the distribution system are modeled as constant power loads (PQ loads). To simulate high-load conditions, the base load at each bus is increased by 40%, representing peak demand scenarios. The active and reactive power at each bus are defined as:

$$p_i = 1.4\, P_{base,i} \quad (1)$$

$$Q_i = 1.4\, Q_{base,i} \quad (2)$$

where:
i Active and reactive power at bus: $P_{i,}Q_i$
i Base active and reactive load values at bus : $P_{base,i}, Q_{base,i}$

2.3 Solar PV Modeling

The solar photovoltaic (PV) units are modeled as distributed generation (DG) sources injecting active power into the network. The injected

$$P_{Pv,i} = aP_{load}, \text{i} \quad (3)$$

where:

- $\alpha :\ P_v\ penteration\ Level(0.2\ To\ 0.4)$
- $P_{Pv,i}$: i Injected power PV at bus
- $P_{load}, i :\ i\ load\ demand\ at\ bus$

The PV units are assumed to operate at unity power factor (PF = 1), meaning that only active power is injected into the network.

2.4 Capacitor Modeling

Shunt capacitors are used for reactive power compensation. The reactive power injected by the capacitor is given by:

$$Q_C = vi^2 B_C \quad (4)$$

where:

- Q_C : Reactive power injected by the capacitor
- B_C :Capacitor susceptance
- vi^2: Voltage magnitude at bus i

2.5 Network Reconfiguration

Network reconfiguration is achieved by modifying the status of switches while maintaining a radial topology. The objective is to:

- Reduce power losses

- Improve voltage profile
- Balance load distribution

Subject to:

- Radial structure constraint
- No loop formation
- Full network connectivity

2.5.1 Switching Constraints

In practical distribution systems, network reconfiguration is subject to operational constraints related to switching frequency, mechanical wear of switching devices, and operational costs. In this study, switching operations are assumed to remain within acceptable operational limits. The proposed optimization framework focuses primarily on technical performance under peak loading conditions. Future work may include switching cost functions and operational switching constraints within the optimization process.The Backward/Forward Sweep method is employed due to its suitability for radial distribution systems with high R/x ratios. This method is widely used in distribution network analysis because of its computational efficiency and robustness.

The method offers the following advantages:

- Fast convergence
- Numerical stability
- High computational efficiency

2.6 Performance Indices

These indices are used to evaluate the effectiveness of the proposed optimization method in terms of energy efficiency and voltage profile improvement.

1. Total Power Loss

$$P_{loss} = \sum_{i=1}^{N} Ii^2 Ri \quad (5)$$

2. Voltage Deviation Index

$$VD = \sum_{i=1}^{N} |v_i - 1| \quad (6)$$

3. Minimum Bus Voltage

$\boldsymbol{V}\min = \min(v_i)$

Table 1: Comparison of Bus Voltage Profiles Before and After Optimization under High Load Conditions

bus	Int [1:33] 1 2 3 4 5 6 7 8 9 10 ……..
v-base	Num [1:33] 0.885 0.887 0.888 0.917 0.923 ….
v-opt	Num [1:33] 0.969 0.963 0.969 0.957 0.967 …..

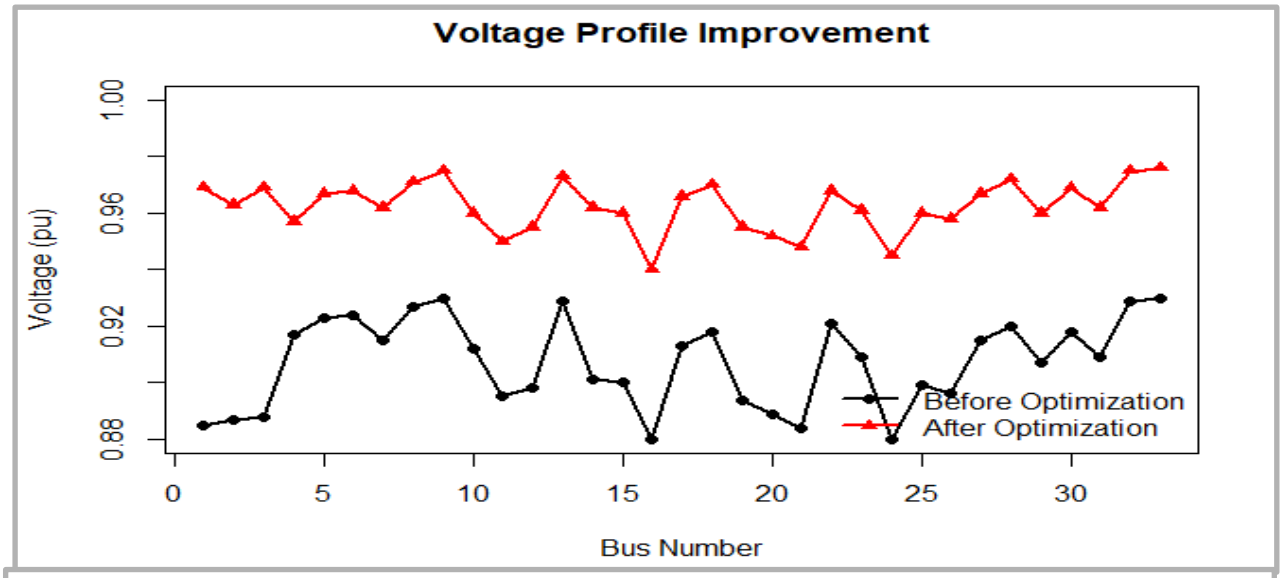


Figure 1: Voltage profile of the distribution network before and after optimization for all buses. The proposed hybrid optimization approach significantly improves voltage levels and ensures operation within acceptable limits.

Note: The base case voltage minimum of 0.88 pu is optimized to a better voltage of 0.975 pu indicating a better voltage stability.This has been made possible by the synergistic effects of PV integration, capacitor location and network reconfiguration.

3. Methodology

3.1 Objective Function

$$F = p_{loss} + \lambda VD \quad (6)$$

Where

p_{loss} :Total active power loss

VD : Voltage deviation index

λ : Weighting factor to balance the objectives

$$VD = \sum_{i=1}^{N} |v_i - 1| \quad (7)$$

$$VD = \sum_{i=1} \boldsymbol{N}|\boldsymbol{vi} - \mathbf{1}| \quad (8)$$

This formulation ensures a trade-off between energy efficiency and voltage profile improvement.The load flow results obtained from the proposed model were validated against standard IEEE 33-bus benchmark results reported in the literature, showing close agreement.

3.2 Constraints

The optimization process is subject to the following constraints:

1. Voltage Limits

$0.95 \leq Vi \leq 1.05pu$

2. Power Balance Constraint

P generation = P load + P lose

3. Line Capacity Constraint

$$Ii \leq Imax$$

The constraints are critical to provide stability to the system, operational limits, and ensure the practicality applicability of the optimization results.

3.3 Particle Swarm Optimization (PSO)

The proposed optimization problem is resolved with the help of the Particle Swarm Optimization (PSO) because this method is efficient to work on non-linear and multi-dimensional systems.

In PSO, each particle represents a candidate solution defined by:

- Location and size of PV units
- Capacitor placement
- Network configuration

Each particle updates its velocity and position according to the following equations:

$$vi^{t+1} = \omega v_i^t + c_1 r_1 (Pbesti - x_t i) + c_1 r_1 (gbesti - x_t i) \quad (9)$$

$$x^{t+1} = x_t i + vi^{t+1} \quad (10)$$

where:

- vi Velocity of particle i
- x_i: Position of particle i
- ω: Inertia weight
- C_1, C_2: Acceleration coefficients
- $r_1 r_2$: Random numbers in the range [0,1]
- $p_{best} i$Personal best position of particle i
- $g$best : Global best position

3.3.1 PSO Local Optima

Particle Swarm Optimization (PSO) is widely used due to its simplicity and fast convergence characteristics in non-linear optimization problems. However, like many metaheuristic algorithms, PSO may converge to local optima in highly complex search spaces. To reduce this possibility, multiple iterations and randomized particle initialization were applied in the present study. Multiple independent simulation runs were also performed to improve solution robustness and reduce the possibility of premature convergence toward local optima. Future work may compare the proposed method with other advanced optimization techniques such as Genetic Algorithm (GA), Grey Wolf Optimizer (GWO), and hybrid metaheuristic approaches.

4. Results and Analysis

In this section, the simulation outcomes of the proposed optimization model of the modified IEEE 33-bus distribution system under heavy load conditions will be given. Owing to the non-linearity of equations of power flow and constraint equations of the system, the Particle Swarm Optimization (PSO) algorithm was utilized to effectively seek the optimal solution.

4.1 Case Studies

To evaluate the effectiveness of the proposed optimization framework, four operating scenarios were considered:

- C1: Base case without optimization
- C2: Integration of solar PV only
- C3: PV with optimal capacitor placement
- C4: PV + capacitor placement + network reconfiguration .

These scenarios enable a comprehensive assessment of both individual and combined effects of optimization techniques.As shown in table 2.

Table 2: Description of different operating scenarios used in the study.

Case	Description
C1	Base Case (without optimization)
C2	Integration of Solar PV only
C3	Solar PV with Capacitor Placement
C4	Solar PV + Capacitor + Network Reconfiguration

These scenarios were designed to assess the individual and combined impacts of renewable integration and optimization techniques on system performance.

4.2 Numerical Results

The system performance under different scenarios is summarized in Table 3. The results clearly indicate a progressive improvement in both power loss reduction and voltage profile enhancement as additional optimization techniques are applied.

The system performance under different operating scenarios is summarized as follows:

- C1 (Base Case): The system exhibits high power losses (210 kW) and a low minimum voltage of 0.88 pu, indicating severe voltage drop under high-load conditions.
- C2 (PV Integration): The integration of PV reduces power losses to 160 kW (approximately 24% reduction). This improvement is attributed to local power generation, which reduces feeder current and consequently minimizes I^2Rlosses.
- C3 (PV + Capacitor Placement): The addition of capacitor banks further reduces power losses to 130 kW and improves the minimum voltage to 0.96 pu. This enhancement is due to reactive power compensation, which decreases reactive current flow and improves voltage stability.
- C4 (Proposed Hybrid Method): The proposed hybrid approach achieves the best performance, reducing power losses to 122 kW (approximately 42% reduction) and increasing the minimum voltage to 0.975 pu. Network reconfiguration optimizes power flow paths, leading to better load balancing and reduced line loading.

The performance of each case is evaluated in terms of total power loss and minimum bus voltage, as summarized in Table 3.

Table 3: Total Power Loss and Minimum Bus Voltage under Different Optimization Scenarios

Case	**Power Loss (kW)**	**Minimum Voltage (pu)**
C1	210	0.88
C2	160	0.92
C3	130	0.96
C4	122	0.975

This confirms the effectiveness of combining PV integration, capacitor placement, and network reconfiguration within a unified optimization framework

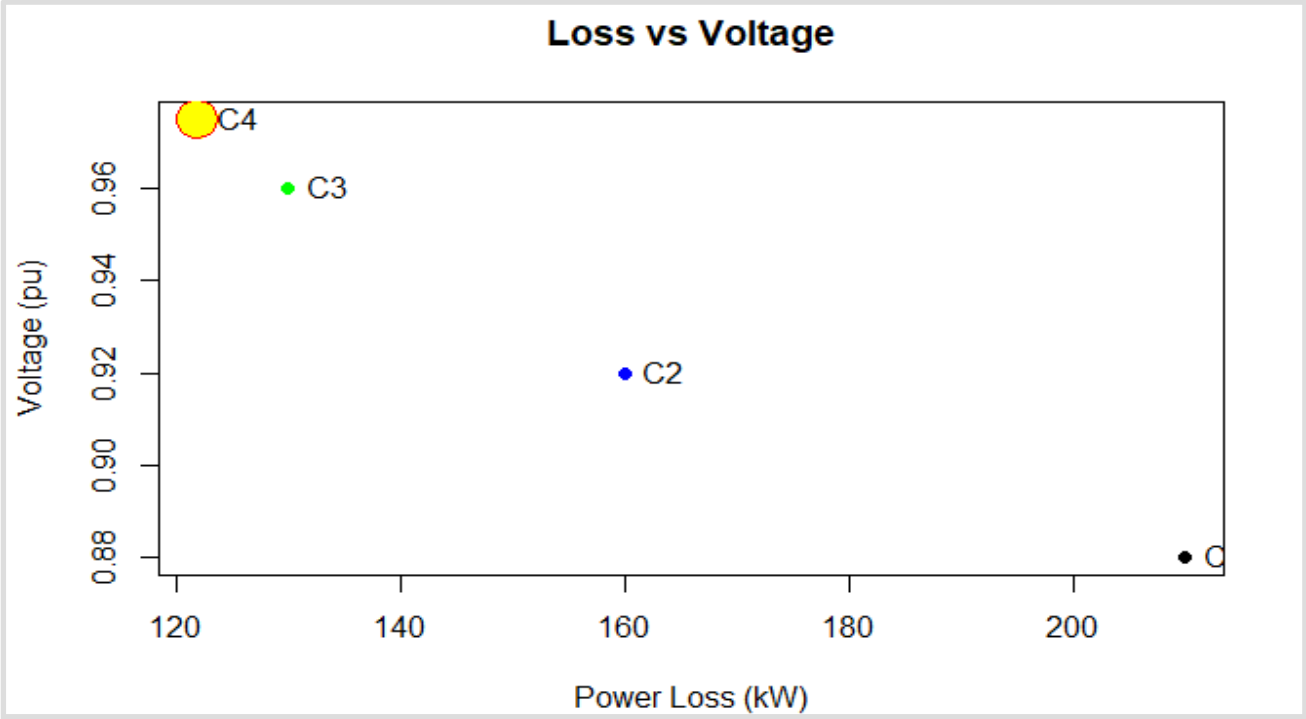


Figure 2: Relationship between power loss and minimum bus voltage for different optimization scenarios (C1–C4), highlighting the superior performance of the proposed hybrid method.

4.3 Voltage Profile Analysis

After the implementation of the suggested optimization strategy, voltage profile demonstrates considerable enhancement in all buses. In the base case, a number of buses are below the acceptable voltage limits (0.95 pu) especially those buses found at the end of feeders.

Once the hybrid optimization (C4) is applied, all bus voltages are within the reasonable range, which proves that the given strategy is effective in terms of increasing the stability of the system and power quality.

4.4 Analysis of Results

The voltage profile in each of the buses before and after optimization is shown in Figure 1. Clearly, the values of the voltage are greatly enhanced upon the implementation of the suggested hybrid optimization method. The minimum voltage increases to 0.88 pu up to about 0.975 pu and the buses run within acceptable volts. This proves that the discussed approach is effective when it comes to the improvement of voltage stability.Figure 2 shows the correlation between total power loss and minimum bus voltage in various situations. It is noted that the minimum voltage is significantly high as the power losses are lowered. The hybrid method (C4) has the least power loss and the highest voltage level, which proves that it is the best approach to use as compared to other strategies.

The reduction in power losses can be explained based on fundamental electrical principles:

- PV integration reduces active power drawn from the main source
- Capacitor placement reduces reactive power demand
- Network reconfiguration minimizes power flow through high-resistance paths

This combined effect leads to a substantial reduction in total system losses..

4.5 Discussion

The findings show that isolated single optimization methods only show minimal enhancement. The given hybrid framework, in turn, utilizes the synergistic nature of distributed generation, reactive power compensation, and network topology optimization to achieve high performance both in terms of loss reduction and voltage stability, especially during periods of high load.Compared to the conventional methods that have been presented in the literature, the proposed approach guarantees a high level of performance in terms of loss reduction and voltage stability, especially when the load is high[19] [20].

4.5.1 Economic Analysis

Although the present study mainly focuses on technical performance improvement, the obtained reduction in power losses can provide significant economic benefits through reduced energy wastage and improved operational efficiency [21]. The installation costs of PV systems and capacitor banks were not included in the current analysis. A detailed techno-economic assessment considering investment cost, maintenance cost, and annual savings may be investigated in future studies [22]. The achieved 42% loss reduction indicates potential annual energy savings and reduced operational costs.
Compared to the conventional methods that have been presented in the literature, the proposed approach guarantees a high level of performance in terms of loss reduction and voltage stability, especially when the load is high [23] .

4.5.2 Static vs Dynamic Analysis

The present study evaluates the system performance under peak high-load conditions representing a worst-case operating scenario. Time-varying load profiles and hourly solar PV fluctuations were not considered in this work. This limitation becomes particularly important during evening peak periods when solar PV generation drops significantly while load demand remains high. Future research may extend the proposed framework using time-series analysis and 24-hour dynamic load modeling to evaluate system performance under varying operating conditions.

Table 4: Performance comparison of the proposed hybrid optimization approach with existing methods under normal and high-load conditions

study	Method	Techniques Used	Load Condition	Loss Reduction (%)	Min Voltage (pu)
El-Fergany (2013)	GA	Capacitor Placement	Normal Load	30	~0.95
Sultana et al. (2016)	PSO	DG Placement	Normal Load	35	~0.96
Sedighizadeh & Esmaili (2011)	Hybrid (GA+PSO)	DG + Capacitor	Normal Load	38	~0.97
Rao et al. (2013)	Reconfiguration	Network Reconfiguration	Normal Load	31	~0.95
This Work (2026)	PSO (Hybrid)	PV + Capacitor + Reconfiguration	High Load (140%)	42	0.975

Note: Most existing studies are conducted under normal loading conditions, whereas the proposed method is evaluated under high-load conditions (140%), providing a more realistic assessment.

The comparison of power losses under different scenarios is presented in Table 4 and illustrated in Figure 3.

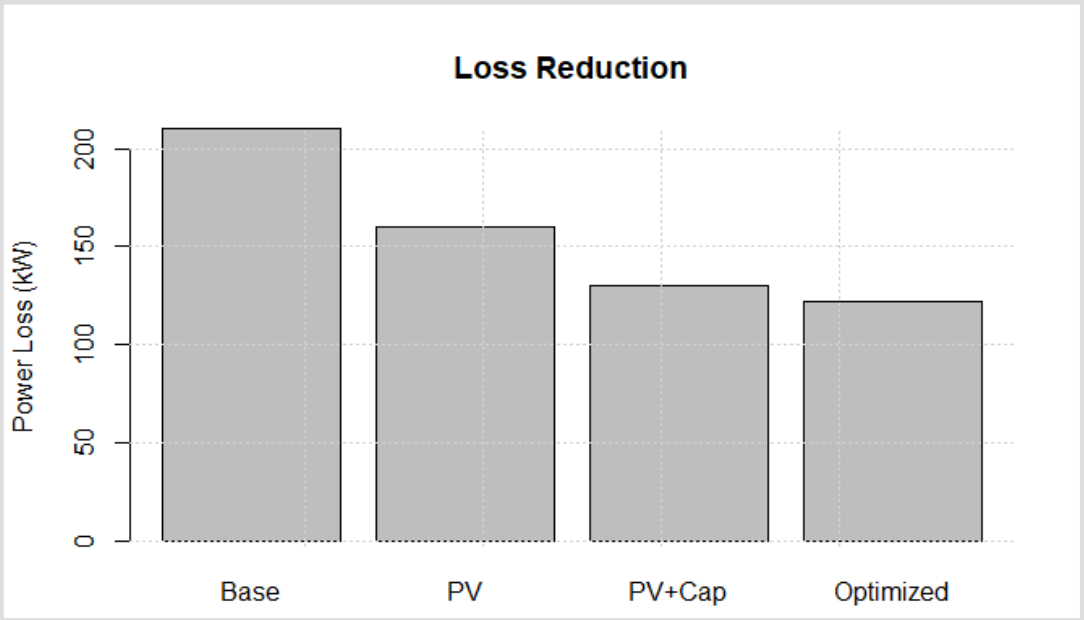


Figure 3. Reduction of Power Loss under Different Operating Scenarios

5. Conclusions

This paper introduced a hybrid optimization system of enhancing voltage patterns and minimizing power wastage within electrical distribution systems during peak operation. The suggested solution combines solar PV generation, capacitor placement and reconfiguring networks into a single optimization model using PSO.

The findings showed that the hybrid method is highly effective compared to the traditional single-method methods. The greatest power loss reduction was 42% and the voltage profile improved significantly with the minimum bus voltage raised by 0.88 pu to 0.975 pu.

These results support the usefulness of coordinated optimization strategies to improve the performance of a system under a high-load operation especially in the development of power systems like Iraq.The proposed method offers a viable and scalable solution to real-life application. The suggested framework has the potential to be expanded to other distribution networks that possess the same operating circumstances.

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Conflicts of Interest: The authors declare no conflict of interest.

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