International Journal of Electrical Components and Energy Conversion
2024, Vol. 10, No. 1, pp. 18-32
https://doi.org/10.11648/j.ijecec.20241001.12

Research Article

Optimal Sizing and Placement of Distributed Generators and Capacitors in Nepal's Sankhu Feeder Using the Water Cycle Algorithm

Yam Krishna Poudel*

Department of Power System Engineering, IoE Pulchowk Campus, Kathmandu, Nepal

Abstract

Minimizing power loss and improving voltage stability are crucial aspects of power systems, driven by transmission line contingencies, financial losses for utilities, and potential power system blackouts. Optimal allocation comprising the sizing and operating power factor—of Distributed Generation (DG) units and capacitor banks (CBs) significantly enhances power system efficiency. Efforts by power system operators and researchers focus on addressing issues related to power loss, energy loss, voltage profiles, and voltage stability through the strategic placement of DGs and CBs. Additionally, optimal DG and CB allocation protects the distribution system from unforeseen events and enables operators to run the system in islanding mode when necessary. The integration of DG units and CBs in distribution systems aims to enhance overall system performance. This research paper introduces a Water Cycle Algorithm (WCA) for the optimal placement and sizing of DGs and CBs. The proposed method targets both technical and economic benefits, considering multiple objective functions: minimizing power losses, reducing voltage deviation, lowering total electrical energy costs, and improving the voltage stability index. The WCA emulates the natural water cycle, from streams to rivers and rivers to the sea. Five different operational scenarios are evaluated to test the performance of this methodology. Simulations are conducted on distribution systems: the IEEE 69-bus test system and the Sankhu feeder network, a real system. The results demonstrate the superior performance of the proposed WCA compared to other optimization algorithms. The findings highlight the WCA's flexibility, efficiency, and significant improvements in economic benefits, establishing it as a promising approach for optimizing the placement of DG and CB in distribution systems.

Keywords

Distributed Generation (DG), Capacitor Bank (CB), Water Cycle Algorithm (WCA), Optimization, Sankhu Feeder Network

1. Introduction

The increasing demand for electrical power and the need for a more reliable and efficient distribution system have necessitated the integration of distributed generation (DG) units and capacitor banks (CBs) in distribution networks. DG units contribute additional power and enhance voltage regulation, while CBs help reduce system losses and improve the power factor. However, determining the optimal placement and sizing of DG and CB units is a complex challenge due to the nonlinear and nonconvex nature of the optimization problem. Various optimization algorithms, such as genetic

*Corresponding author: yampd01@gmail.com (Yam Krishna Poudel)

Received: 25 September 2024; **Accepted:** 22 October 2024; **Published:** 22 November 2024

algorithms, particle swarm optimization, and differential evolution, have been proposed in recent years to tackle this issue (Poudel, Pudasaini, et al., [12], (Poudel & Bhandari, [11]).

Utilities in developing and under-developed countries often face capital shortages for generation and transmission systems amidst disproportionate load growth. The efficiency of a power system is closely linked to the performance of its transmission and distribution networks. High power losses in these systems reduce overall efficiency and result in financial losses for utilities. By minimizing power losses, utilities can increase revenue. For those with limited capital, effectively utilizing existing infrastructure with minimal enhancements can offer two key benefits: it delays the need for significant capital investment to upgrade the system, and it generates additional revenue that can help fund future system reinforcements [15-17]. Following the deregulation and privatization of power systems, a common issue in distribution networks is the insufficient availability of reactive power sources. Reactive power generated by distributed generators can alleviate the demand for reactive power from the grid. Power flows in distribution lines can lead to significant power losses, voltage drops, and poor power factors at load ends. Proper allocation of capacitors, either alone or in combination with DG sources, can effectively mitigate these problems (Poudel, Kumar Pudasaini, et al., [13]), (Mahato et al., [9]).

2. Literature Review

The paper publishes by (Judge et al., [8]), (Ayadi et al., [4]), (Poudel, Kumar Pudasaini, et al., [12]), (Poudel, Pudasaini, et al., [13]),(Ibrahim et al., [7]), (Abdulnasser et al., [1]), (Alwash et al., [3]), (Sambaiah, [14]), (Ali et al., [2]), (Dagade et al., [5]), (Hajar Alimorad, [6]), (Eskandar et al., [10]) are taken for our foundation's and the work done by them are summarized in below.

1. Optimization Techniques for Distributed Generation and Capacitor Banks

Abdulnasser, Ali, and Mohamed [1] presented an approach for the optimal planning of distributed generation and capacitor banks in distribution networks. Their study emphasized the importance of strategic placement and sizing of these components to reduce power losses and improve voltage profiles. They employed a multi-objective optimization framework, which considered various technical and economic factors, demonstrating significant improvements in network performance.

Ali et al. [2] expanded on this by considering the effect of voltage-dependent nonlinear load models. Their study used advanced multi-objective optimization techniques to determine the optimal siting and sizing of DGs and shunt capacitors, achieving a more resilient and efficient power distribution system. Their findings highlighted the critical role of accurate load modeling in optimization studies, which can significantly impact the effectiveness of DG and capacitor bank integration.

Eskandar et al., [10] introduced the Arithmetic Optimization Algorithm for the optimal allocation of distributed generations and capacitor banks. Their approach was tested on real distribution systems, proving effective in minimizing power losses and enhancing voltage stability. This study provided a robust comparison with other optimization techniques, positioning the Arithmetic Optimization Algorithm as a promising tool for real-world applications.

Hajar Alimorad [6] conducted a comparative analysis of recently developed metaheuristic optimization techniques on the real distribution networks of Algeria. Their study offered valuable insights into the performance of various algorithms, identifying the most effective methods for specific network configurations. This work is particularly relevant for practitioners seeking to implement optimization techniques in diverse operational environments.

2. Impact of Renewable Energy Integration

Ayadi et al. [4] explored the impacts of renewable energy resources on smart grids. Their research underscored the challenges and opportunities associated with integrating large-scale renewable energy sources, such as solar and wind, into existing power distribution networks. They discussed the need for advanced control strategies and optimization techniques to manage the intermittent nature of renewable energy, ensuring stability and reliability in smart grids.

Sambaiah [14] focused on the allocation of renewable energy sources within electrical distribution systems using the Water Cycle Algorithm. This study highlighted the potential of renewable energy to reduce dependency on conventional power sources, lower emissions, and enhance grid resilience. By optimizing the placement of renewable energy sources, the study demonstrated significant reductions in power losses and improvements in overall system efficiency.

3. Network Reconfiguration and Loss Reduction

Ibrahim, Alwash, and Aldhahab [7] proposed an enhanced Water Cycle Algorithm for optimal network reconfiguration and DG integration. Their research aimed at minimizing power losses and improving voltage profiles in power distribution systems. The study demonstrated that strategic reconfiguration, combined with DG integration, could lead to substantial efficiency gains.

Alwash, Ibrahim, and Abed [3] further developed this concept by integrating a Soft Open Point (SOP) for power loss reduction. Their study presented a novel approach to distribution system reconfiguration, showing how SOPs can be effectively utilized in conjunction with advanced optimization techniques to enhance network performance.

Dagade, Dagade, and Godha [5] focused on the optimal allocation of photovoltaic (PV) based DG and capacitors in radial distribution networks. Their study employed a comprehensive optimization framework, demonstrating how PV systems and capacitors can be strategically integrated to minimize power losses and improve voltage stability. This research is particularly relevant in the context of increasing

PV adoption in distribution networks.

4. Smart Grid Implementation

Judge et al. [8] provided an overview of smart grid implementation, discussing various frameworks, impacts, and challenges. Their review highlighted the transformative potential of smart grids in modernizing power distribution systems, enabling more efficient and reliable energy management. The study also identified key challenges, including cybersecurity risks, integration of distributed energy resources, and the need for advanced communication infrastructures.

5. Innovative Applications and Future Directions

Poudel et al. [12] explored the design of high-frequency transformers for solid-state transformers in electric power distribution systems. Their novel design methodology addresses the growing need for efficient and compact power conversion devices in modern distribution networks. This study represents a significant advancement in transformer technology, with implications for the future of power distribution.

In another study, Poudel, Pudasaini, et al. [13] investigated the integration of battery and super capacitor-based hybrid energy storage systems with photovoltaic (PV) systems in islanded DC MicroGrids. Their research provided a comprehensive analysis of the performance and reliability of hybrid storage systems, offering insights into their potential for enhancing energy security in isolated communities.

Mahato et al. [9] examined power loss minimization and voltage profile improvement in radial distribution networks through the installation of capacitors and DGs. Their study employed a rigorous optimization approach, demonstrating the effectiveness of these technologies in enhancing the operational efficiency of distribution networks.

The profound efficacy of diverse optimization algorithms in the strategic placement and sizing of Distributed Generation (DG) units and Capacitor Banks (CBs) within distribution systems. These advanced methodologies have been shown to markedly improve the operational performance of distribution networks. By optimizing the allocation and sizing of DG units and CBs, these approaches not only enhance voltage stability, minimize power losses, and optimize power quality but also facilitate the seamless integration of renewable energy sources. This, in turn, fosters a more reliable, efficient, and sustainable power system architecture, aligning with contemporary energy demands and sustainability goals. Furthermore, these methodologies contribute to the resilience of power grids, aiding in the transition towards greener and smarter energy solutions.

3. Research Methodology

Problem formulation

I) Objective Function (OF)

The proposed method aims to achieve two types OFs: technical and economic OFs.

Technical OF: Three technical OFs are considered in this section. The first one aims to minimize the distribution power losses (f_1) that can be expressed as

$$f_1(x) = min\sum_{i=1}^{nL} R_i * |I_i|^2 \quad (1)$$

The second technical OF aims to improve the voltage profile and preserve better voltage profile. The function can be described as

$$f_2(x) = min\sum_{i=0}^{N} \frac{(V_i - V_i^{spec})}{\left(V_i^{max} - V_i^{min}\right)^2} \quad (2)$$

The voltage stability is one of the most significant indices. The third OF (f_3) for the voltage stability index (VSI) can be described as

$$f_3(x) = \min \frac{1}{VSI(m_2)} \quad (3)$$

Where VSI (m_2) is voltage stability index at node 2.

$$VSI(m_2) = ABS(|V(m_1)|^4 - 4 * \left[P(m_2) * X_{ij} - Q(m_2) * Rij\right]^2 - 4 * \left[P(m_2) * R_{ij} + Q(m_2) * X_{ij}\right] * |V(m_1)|^2$$

For the stable operation of radial distribution networks, VSI (m_2) ≥ 0. The node at which the value of stability index is minimum, is more sensitive to the voltage collapse.

Economic OF: The economical OF (f_4) aims to minimize the power generation costs that can be calculated from

$$f_4(x) = min\sum_{i=1}^{N_{DG}}(C_{DGi} + C_{sub} + C_{CB} \quad (4)$$

At first, for DG,

$$C_{DGi} = \sum_{i=1}^{N_{DG}}(a + b * PG_i$$

Where,

$$a = \frac{capital\ cost\left(\frac{\$}{\text{kw}}\right) * \text{capacity(kw)} * G_r}{life\ time(year) * 8760 * LF}$$

where, G_r= annual rate of benefit

LF= DG loading factor

$PG_{i=}$ Energy generated by DG.

$$\eta = G_r/(life\ time(year) * 8760 * LF = 1.3(constant)$$

$$b = O\&M\ cost\left(\frac{\$}{\text{kwh}}\right) + \text{fuel cost}\left(\frac{\$}{\text{kwh}}\right)$$

$$C_{sub} = \sum_{i=1}^{N_{DG}}(P_{sub} * Pr_{sub})$$

Where, P_{sub} = power production at substation

Pr_{sub} = cost of power generated at substation (taken 0.044$/kWh)

C_{sub}= cost of electrical energy generation by each source

Similarly, for capacitor

$$C_{CB} = \sum_{i=1}^{N_c} \frac{(e_i + C_{ci} * Q_{ci})}{8760 * life\ time}$$

Where, $\frac{1}{life\ time * 8760}$ act as depreciation rate over its life time period

e_i= fixed VAR source installation cost at bus i taken equal to 1000

C_{ci}= corresponding purchase cost taken equal to 30,000 $/MVar

Q_{ci}= reactive power of existing VAR sources installed at bus i

N_C= reactive compensator bus

Constraints:

Equality constraints: The constraints for power balance requirements:

$$\sum_{i=1}^{N_G} PG_i - P_L = P_d$$

$$\sum_{i=1}^{N_G} QG_i - Q_L = Q_d$$

Inequality constraints: Maximum admissible generated power from DGs/CBs should not exceed to permissible limitations of the distribution systems.

Generation operation Limits

$$PG_i^{min} \le PG_i \le PG_i^{max}, QG_i^{min} \le QG_i \le QG_i^{max}$$

Install capacitor limits

$$Q_{CB}^{total} < Q_d$$

Bus voltage limits

$$0.95 \le V_i \le 1.05, i = 1,2,3, \dots .n\ bus$$

DG power factor limits

$$0.8 \le PF \le 1$$

II) Case Study

Cases Studied:

For the proper analysis, five operational cases were studied using Water Cycle Algorithm. It helps to understand the adequacy of the proposed algorithm over other algorithms.

1. Case 1: Power loss minimization (f_1) by optimal placement of Capacitors only.

$OF = minimize(f_1)$

The Streams contain 2n number of Raindrops, n being the number of Capacitors to be inserted into the network. First n Raindrops store the bus location of Capacitors, and the second n Raindrops store the KVar size of those Capacitors.

2. Case 2: Power loss minimization (*f1*) by allocating DGs that operate at unity PF.

$OF = minimize(f_1)$

The Streams contain 2n number of Raindrops, n being the number of DGs to be inserted into the network. First n Raindrops store the bus location of DGs, and the second n Raindrops store the MW size of those DGs.

3. Case 3: Power loss minimization (f_1) by allocating the combination of CBs, and DGs operating at unity pf.

$OF = minimize(f_1)$

The Streams contain 2m+2n number of Raindrops, m being the number of Capacitors, and n being the number of DGs to be inserted into the network. First m Raindrops store the bus location of Capacitors, next m Raindrops store the KVar size of Capacitors, next n Raindrops store bus location of DGs, and the next n Raindrops store the MW size of those DGs.

4. Case 4: Power loss minimization (f1), voltage profile improvement (f2), and minimum VSI enhancement (f3) by allocating the combination of CBs, and DGs with adjustable power factor.

$$OF = minimize(w_1 * f_1 + w_2 * f_2 + w_3 * f_3)$$

where, w_1, w_2, and w_3 are weighing factors of f_1, f_2, and f_3 respectively.

In this analysis, w_1, w_2, and w_3 are taken as 0.5, 0.25, and 0.25 respectively. The Streams contain 2 m+3 n number of Raindrops, m being the number of Capacitors, and n being the number of DGs to be inserted into the network. First m Raindrops store the bus location of Capacitors, next m Raindrops store the KVar size of Capacitors, next n Raindrops store bus location of DGs, the next n Raindrops store the MW size of DGs, and the last n Raindrops store the operating power factor of those DGs. In this research work, maximum of three Capacitor banks, and three DGs were incorporated in the distribution network.

5. Case 5: Power loss minimization (f1), and cost minimization (f4) by allocating the combination of CBs, and DGs with adjustable power factor.

$$OF = minimize(w_1 * f_1 + w_4 * f_4)$$

where, w_1, w_4 are weighing factors of f_1, and f_4 respectively.

In this analysis, w_1, and w_4 are taken as 0.75, and 0.25 respectively. The Streams contain $2m + 3n$ number of Raindrops, m being the number of Capacitors, and n being the number of DGs to be inserted into the network. First m Raindrops store the bus location of Capacitors, next m Raindrops store the KVar size of Capacitors, next n Raindrops store bus location of DGs, the next n Raindrops store the MW size of DGs, and the last n Raindrops store the operating power factor of those DGs. In this research work, maximum of three Capacitor banks, and three DGs were incorporated in the distribution network [2].

Flow Chart of WCA model

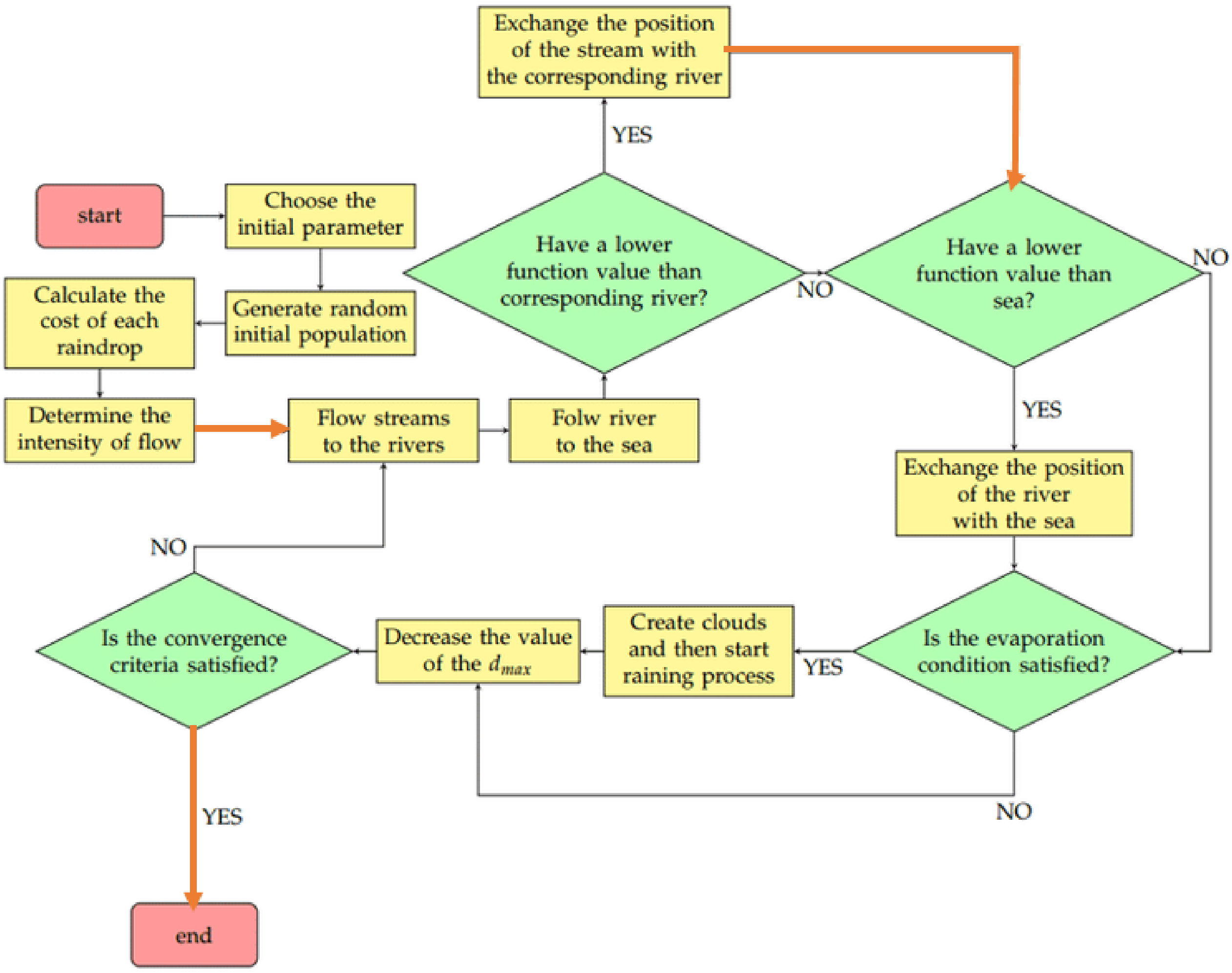

Figure 1. *Flow Chart of WCA model.*

Detailed steps in WCA:

WCA is a natural water-cycle inspired optimization algorithm, based on downhill flow of rivers and streams into the sea. WCA begins with an initial population similar to other metaheuristic algorithms, this initial population called the raindrops (RD) [18-22].

The values of the problem controlled variables x_i (PG_i, QG_i, Q_{CB}^{total}, and placement of DG and CB) can be formed as an array called "RD" for single solution. This array can be defined as follows:

$$RD = [x_1, x_2, x_3, \dots . x_N]$$

Each set of solution is called a Stream, the Stream with the best fitness is chosen as the Sea, and a fixed number of Streams with better fitness values are designated as Rivers. Rivers and the Sea take water from various Streams — which Stream flow into which River or the Sea is determined by the intensity of flow NS_n.

$$NS_n = round\left\{\left|\frac{ff_n}{\sum_{i=1}^{NS_r} ff_i}\right| * N_{pop}\right\}, n = 1,2,3, \dots . N_{sr}$$

Where,

NS_n is the number of Streams that flow into specific Rivers and the Sea,

N_{pop} is the total number of Streams considered,

N_{sr} is the combined number of the Sea and Rivers

The fitness of any stream is given by:

$$ff_i = f(x_1^i, x_2^i, x_3^i, \dots \dots x_{Nvar}^i), i = 1,2,3, \dots . Npop$$

Streams flow into the Rivers, and Rivers flow into the Sea using a randomly generated distance as shown below:

$$X_{stream}^{i+1} = X_{stream}^{i} + rand * U * (X_{river}^{i} - X_{stream}^{i})$$

$$X_{river}^{i+1} = X_{river}^{i} + rand * U * (X_{sea}^{i} - X_{river}^{i})$$

Where, $1 < U < 2$ and the best value of U is chosen as 2 and rand is a uniformly distributed random number between 0 and 1.

If the fitness of any Stream is better than the associated River, then they exchange the roles. Same is the case with

Rivers and the Sea. Next, evaporation is introduced into the algorithm to prevent trapping of solution in the local optima. Rivers and Streams are checked for close proximity to the Sea for evaporation to occur using:

$$\left|X_{sea}^{i}-X_{river}^{i}\right|<d_{max},i=1,2,3,\ldots\ldots,N_{sr}-1$$

$$\left|X_{sea}^{i}-X_{stream}^{i}\right|<d_{max},i=1,2,3,\ldots\ldots,N_{s}$$

Where d_{max} is very small value close to zero.

Raining process is applied after evaporation. Raining process after evaporation of Rivers generate new Streams using:

$$X_{new\ stream}^{i+1}=LB+rand*(UB-LB)$$

Where, LB and UB are lower and upper boundaries respectively

And, raining process after evaporation of Streams generate new Streams using:

$$X_{new\ stream}=X_{sea}+sqrt(\mu)*rand(1,N_{var})$$

Where, μ is a coefficient (taken as 0.1) showing the searching range in the regions near the sea (larger value can move the search away from the optima and lower value may confine the search in small area), and rand is the normally distributed random number from 0 to 1.

After the end of every evaporation process, the value of d_{max} is updated as follows:

$$d_{max}^{i+1}=d_{max}^{i}-\left(\frac{d_{max}^{i+1}}{max}.iteration\right)$$

In ER-WCA, some Rivers having low flow because of lesser Streams pouring into them have lower potential to become the Sea, so they evaporate. The evaporation rate (ER) for Rivers is calculated using:

$$ER=\frac{SUM(NS_{n})}{N_{sr}-1}*rand,n=2\ldots\ldots,N_{sr}$$

It should be noted that higher flow Rivers have lower evaporation rate and lower flow Rivers have higher evaporation rate. Also, there are two evaporations in each cycle in ER-WCA — first of Rivers/Streams when reaching the Sea; second of Rivers having lower flow because of lesser streams pouring into those rivers. In short, ER-WCA has an ability to effectively search for the best solution in the global space.

4. System under Consideration

The test system are IEEE 69- bus test system and Sankhu feeder network of INPS as a real system.

Sankhu feeder network:

The Sankhu Feeder Network is an integral part of the Nepal Electricity Authority's (NEA) distribution system, serving the Sankhu area in Nepal. Located in the northeastern part of the Kathmandu Valley, this network spans approximately 16.2 square kilometers. It consists of a single 33 kV transmission line that supplies power to four 11 kV substations, which further distribute electricity to various 11 kV and 400 V feeders Serving a diverse customer base, the Sankhu Feeder Network includes about 14,000 residential, commercial, and industrial customers. The network experiences a peak demand of approximately 10 MW and an average demand of around 5 MW. However, it faces several challenges, including high losses, voltage regulation issues, and reliability problems.

Results for IEEE 69-bus system:

The results of load flow is tabulated below.

Table 1. *Result obtained from the base case.*

For Base case	
Minimum bus voltage (pu)	0.909 (65)
Active power loss (kw)	225.001
Reactive power loss (kvar)	102.165
Power factor	0.821

Table 2. *Summary of Load flow report for IEEE 69- bus system.*

IEEE-69 BUS SYSTEM	**ACHIEVED RESULTS**	**REFERENCE PAPER RESULTS**	
Case I (capacitors only)	**WCA**	**GSA**	**PSO**
Minimum voltage	0.932 (62)	0.952	0.934
Active Power loss (KW)	145.49	145.90	152.48
Reactive Power loss (KVar)	67.798		
Loss reduction (%)	35.34	35.16	32.23

IEEE-69 BUS SYSTEM	**ACHIEVED RESULTS**	**REFERENCE PAPER RESULTS**	
Case I (capacitors only)	**WCA**	**GSA**	**PSO**
Placement capacitor (MVar)	0.425 (53), 0.312 (18), 1.205 (61)	0.15 (26), 0.15 (13), 1.050 (15)	1.015 (59), 0.241(61),0.365 (65)
Case II (only DGs)	WCA	CVSI	GA
Minimum voltage	0.979(64)	0.968 (27)	0.969
Active Power loss (KW)	69.428	83.18	88.50
Reactive Power loss (KVar)	34.962		
Loss reduction (%)	69.14	63.03	60.67
Placement DG (MW)	1.719 (61), 0.526 (11), 0.380 (18)	1.895 (61)	1.9471

Table 3. Results of different cases studied on IEEE 69- bus system.

IEEE-69 BUS SYSTEM	**ACHIEVED RESULTS**	**REFERENCE PAPER RESULTS**	
Case III (Capacitors and DGs with unity pf simultaneously)	**WCA**	**DICA**	
Minimum voltage	0.985 (66)	0.979	
Active Power loss (KW)	12.681	17.20	
Reactive Power loss (KVar)	10.012		
Loss reduction (%)	94.36	92.36	
Placement of capacitor (MVar)	0.023 (34), 1.5 (36), 1.298 (61)	0.35 (11), 0.25 (20)	
Placement of DG (MW)	0.380 (64), 1.309 (61), 0.795 (12)	2.25	
IEEE-69 BUS SYSTEM	ACHIEVED RESULTS	IEEE-69BUS SYSTEM	ACHIEVED RESULTS
Case IV (Capacitors and DGs with controllable pf simultaneously) for only technical objectives	WCA	Case V (Capacitors and DGs with controllable pf simultaneously) for techno- economic objectives	WCA
Minimum voltage	0.987 (61)	Minimum voltage	0.931 (64)
Active Power loss (KW)	8.455	Active Power loss (KW)	145.066
Reactive Power loss (KVar)	6.501	Reactive Power loss (KVar)	67.249
Loss reduction (%)	96.24	Loss reduction (%)	35.53
Placement of capacitor (MVar)	0.568 (49), 0.267 (18)	Placement of capacitor (MVar)	1.237(61),0.337(66),0.266 (18)
Placement of DG (MW)	0.864 (66), 1.244 (2), 2.073 (61)	Placement of DG (MW)	2.281 (2), 2.066 (3), 2.281(4)
Power factor of DGs	0.932, 1, 0.815	Power factor of DGs	1, 0.945, 0.959

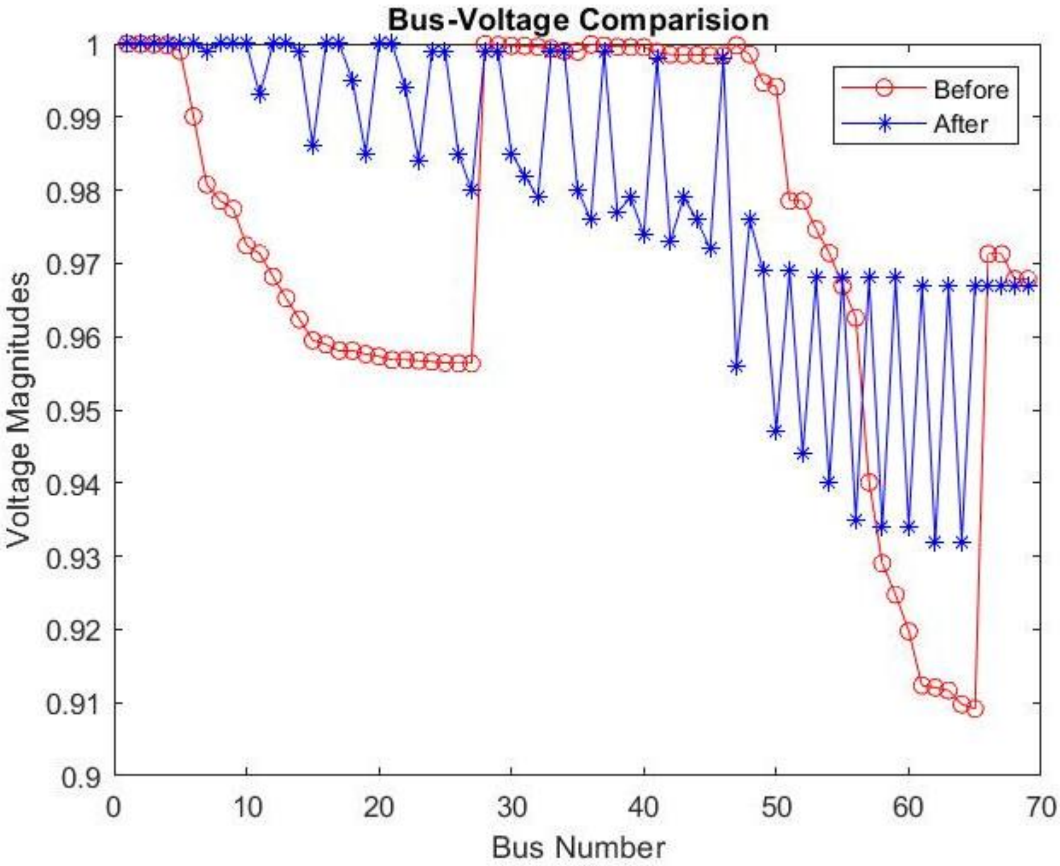

Figure 2. *Bus Voltage comparison of case I (capacitors only) for IEEE 69-Bus System.*

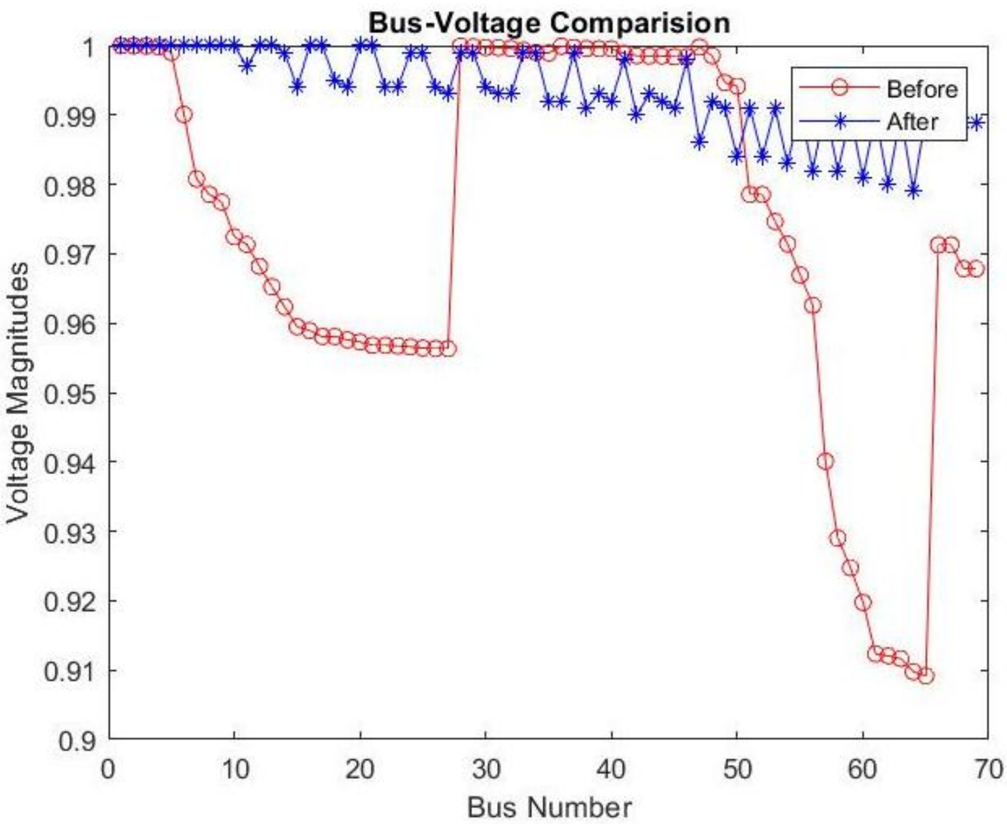

Figure 3. *Bus voltage comparison of case II (DGs only) for IEEE 69-Bus System.*

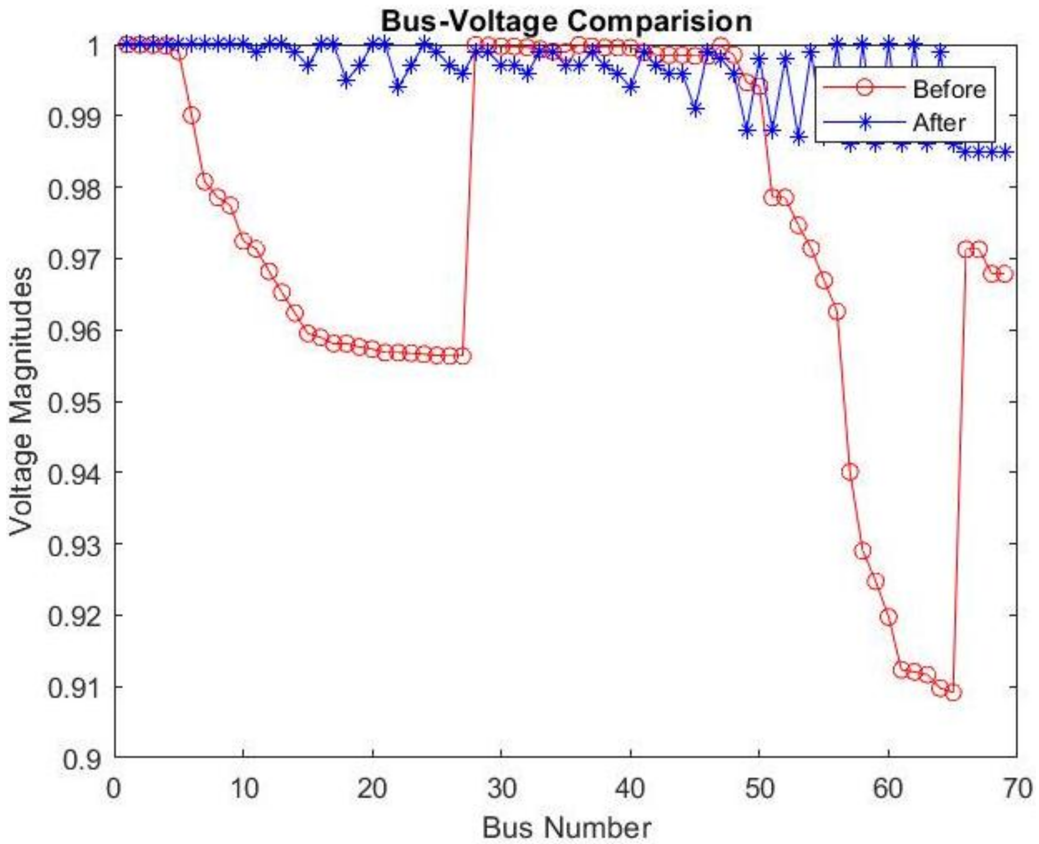

Figure 4. *Bus voltage comparison of Case III (Capacitors and DGs with unity pf simultaneously) for IEEE 69-Bus System.*

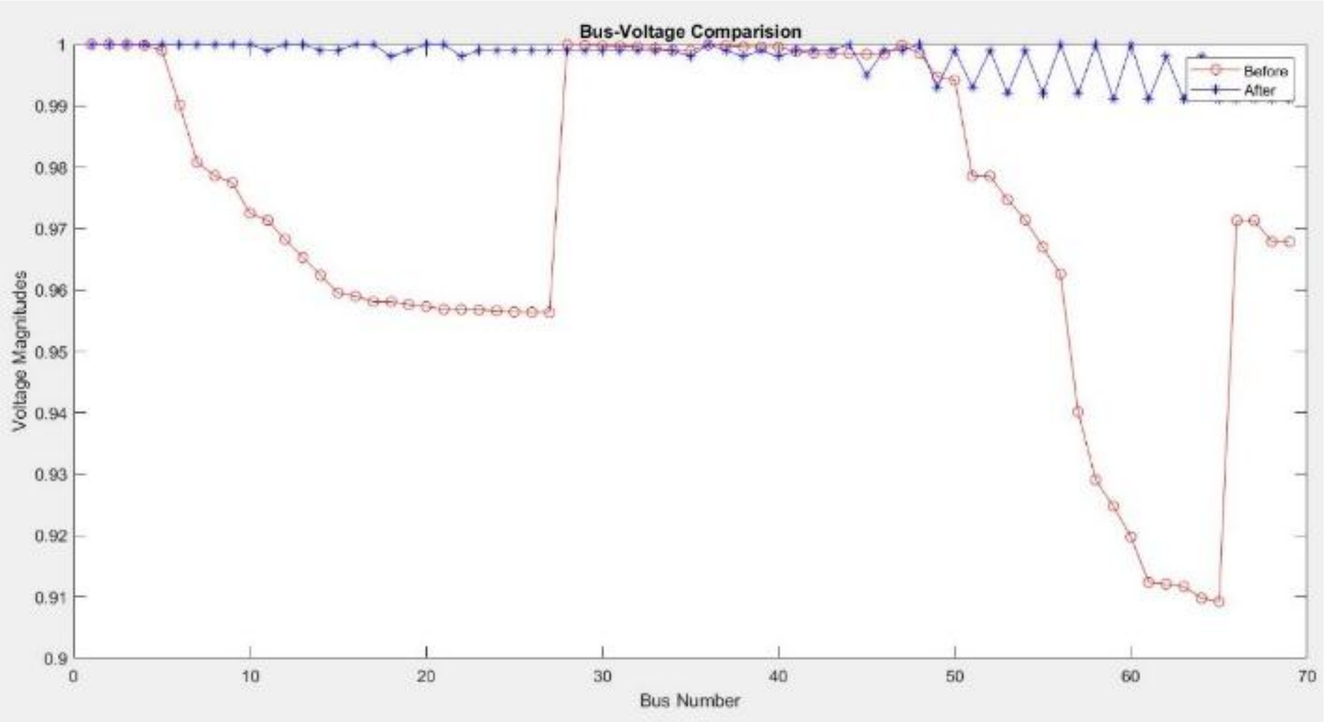

Figure 5. *Bus voltage comparison of Case IV (Capacitors and DGs with controllable pf simultaneously) for only technical objectives for IEEE 69-Bus System.*

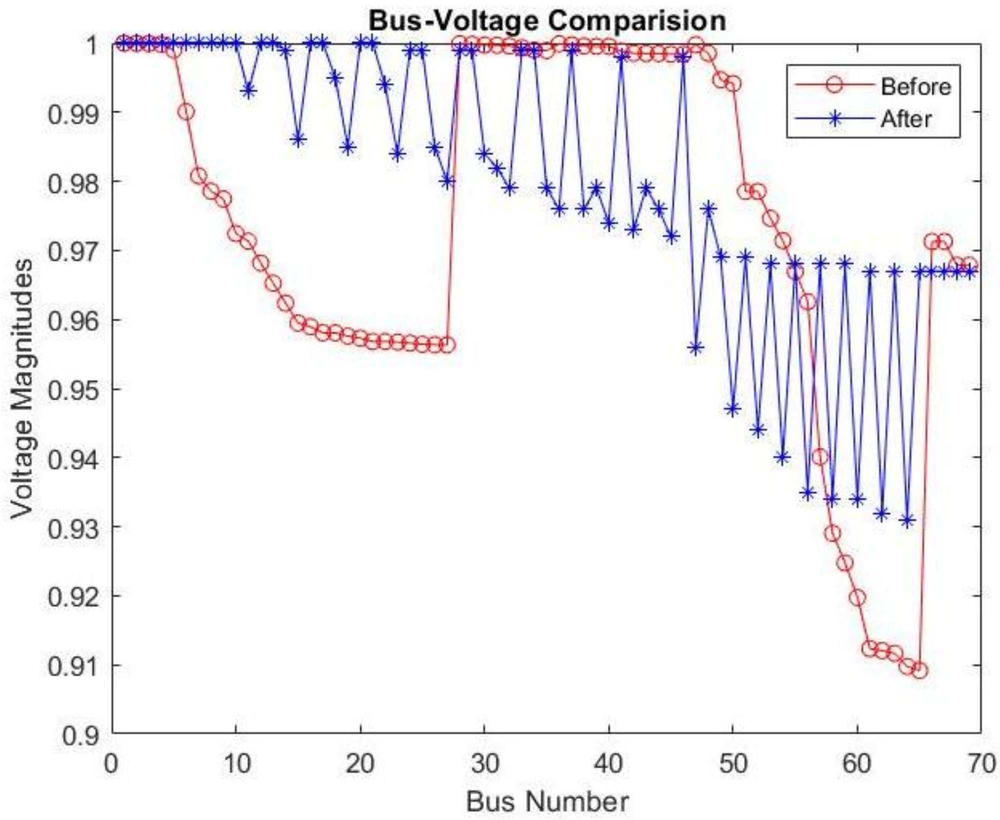

Figure 6. Bus voltage comparison of Case V (Capacitors and DGs with controllable pf simultaneously) for techno- economic objectives for IEEE 69-Bus System.

Results for Sankhu feeder network:
The results of load flow tabulated as below

Table 4. Result obtained from the Sankhu feeder base case.

For Base case	
Minimum bus voltage (pu)	0.809 (37)
Active power loss (kw)	1296.991
Reactive power loss (kvar)	345.701
Power factor	0.757

Table 5. Results of different cases studied on Sankhu feeder network.

Sankhu feeder system	Achieved Results
Case I (capacitors only)	WCA
Minimum voltage (pu)	0.821 (52)
Active Power loss (KW)	1037.276
Reactive Power loss (KVar)	276.476
Loss reduction (%)	20.024

Sankhu feeder system	**Achieved Results**
Placement capacitor (KVar)	435.3224 (24), 420.3678 (3), 330.3348 (30)
Sankhu feeder system	Achieved Results
Case II (DGs only)	WCA
Minimum voltage (pu)	0.955 (50)
Active Power loss (KW)	519.332
Reactive Power loss (KVar)	138.423
Loss reduction (%)	59.96
Placement DG (MW)	0.97736 (17), 1.9638 (22), 1.4295 (31)
Sankhu feeder system	Achieved Results
Case III (Capacitors and DGs with unity pf simultaneously)	WCA
Minimum voltage (pu)	0.986 (50)
Active Power loss (KW)	64.064
Reactive Power loss (KVar)	17.076
Loss reduction (%)	95.02
Placement capacitor (KVar)	1000 (33), 1000 (22), 1000 (27)
Placement of DG (MW)	1.5933 (30), 1.2331 (44), 1.5708 (19)
Sankhu feeder system	Achieved Results
Case IV (Capacitors and DGs with controllable pf simultaneously) for only technical objectives	WCA
Minimum voltage (pu)	0.993 (9)
Active Power loss (KW)	17.752
Reactive Power loss (KVar)	4.732
Loss reduction (%)	98.63
Placement capacitor (KVar)	428.9224 (34), 1000 (12), 802.6335 (29)
Placement DG (MW)	0.94534 (47), 2.6617 (21), 1.2381 (33)
Power factor of DGs	0.8, 0.82763, 0.97458
Sankhu feeder system	Achieved Results
Case V (Capacitors and DGs with controllable pf simultaneously) for techno- economic objectives	WCA
Minimum voltage (pu)	0.903 (52)
Active Power loss (KW)	308.149
Reactive Power loss (KVar)	82.134
Loss reduction (%)	76.24
Placement capacitor (KVar)	1000 (27), 1000 (33), 1000 (45)
Placement DG (MW)	0.49 (2), 2.6116 (3), 2.94 (7)
Power factor of DGs	0.8, 0.93285, 0.94519

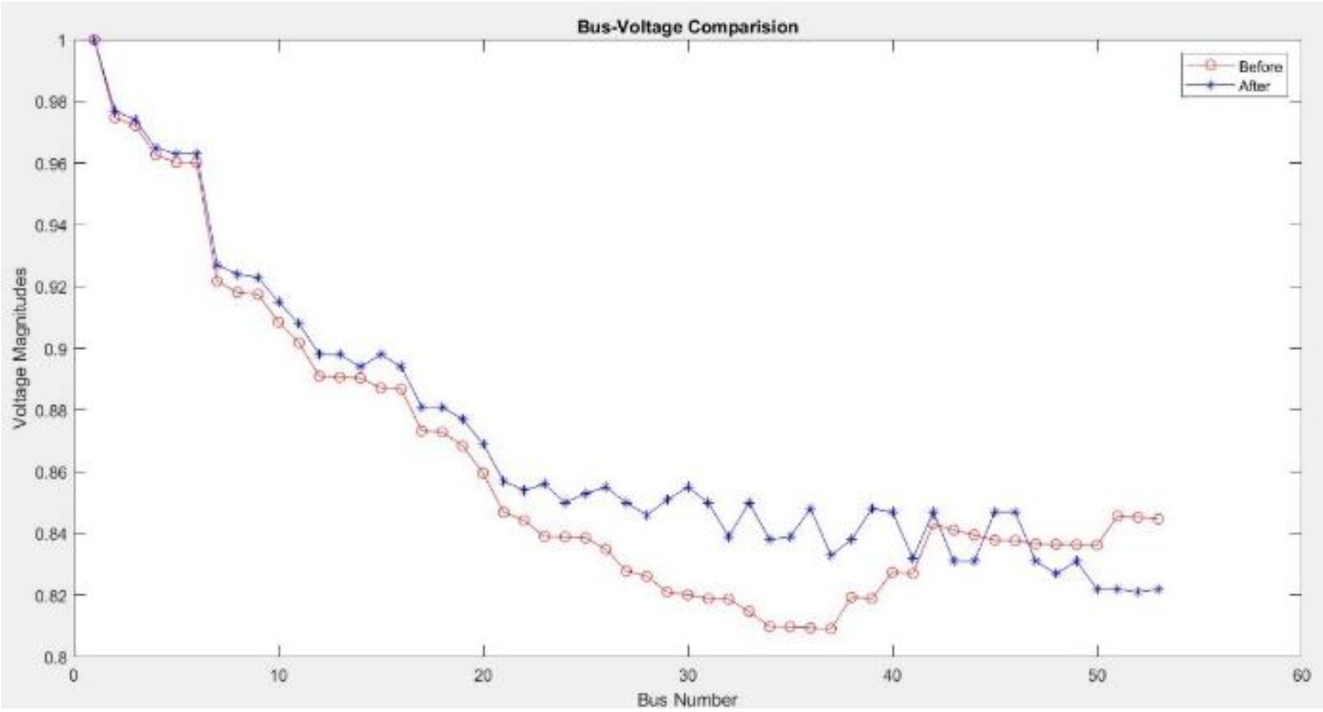

Figure 7. *Bus Voltage comparison of case I (capacitors only) for Sankhu feeder network.*

The Figure 7 shows the comparison of voltage profile improvement before and after the capacitor placement. After the placement of capacitor, the voltage profile seems improving from 0.82 to 0.85. significant change is appearing in the bus between 20 to 40 buses and voltage level degrade after 50 buses.

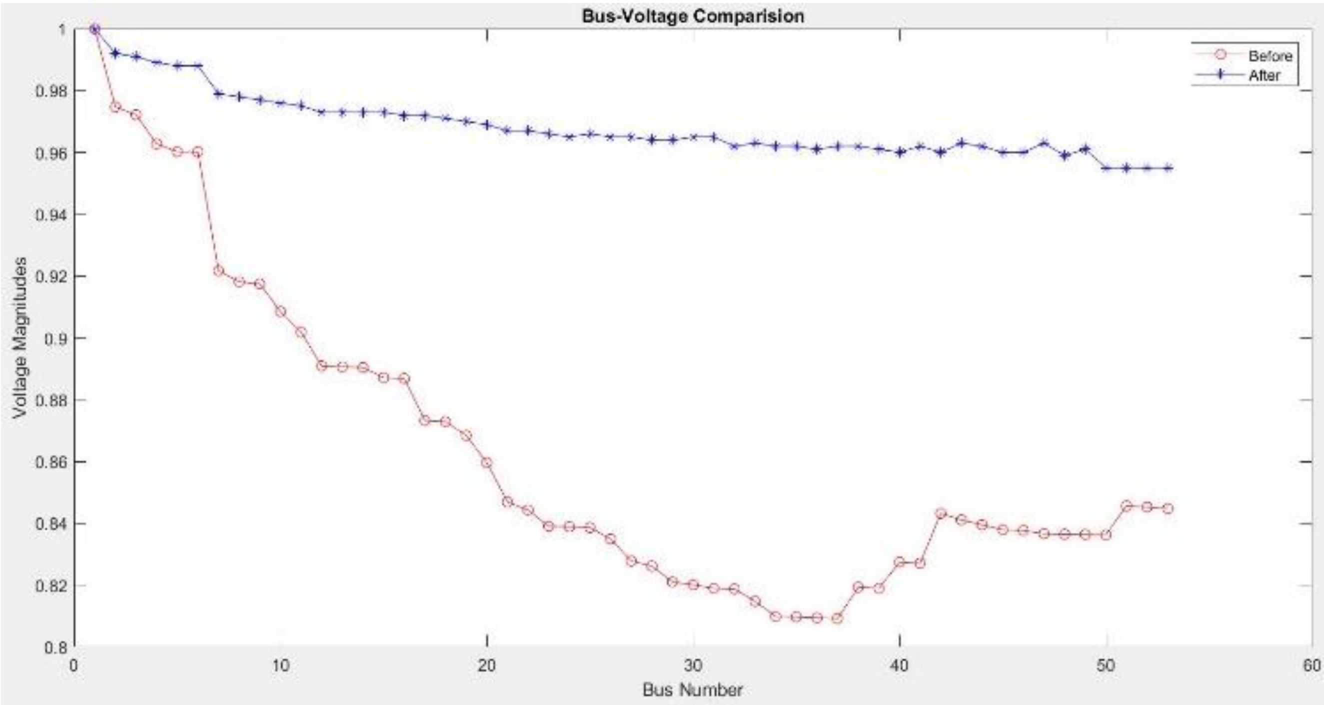

Figure 8. *Bus voltage comparison of case II (DGs only) for Sankhu feeder network.*

The Figure 8 shows the bus voltage comparison of injecting the distributed generations for Sankhu feeder network. After injecting the distributed generations, the voltage profile of sakhu feeder increase from 0.82 to 0.96.

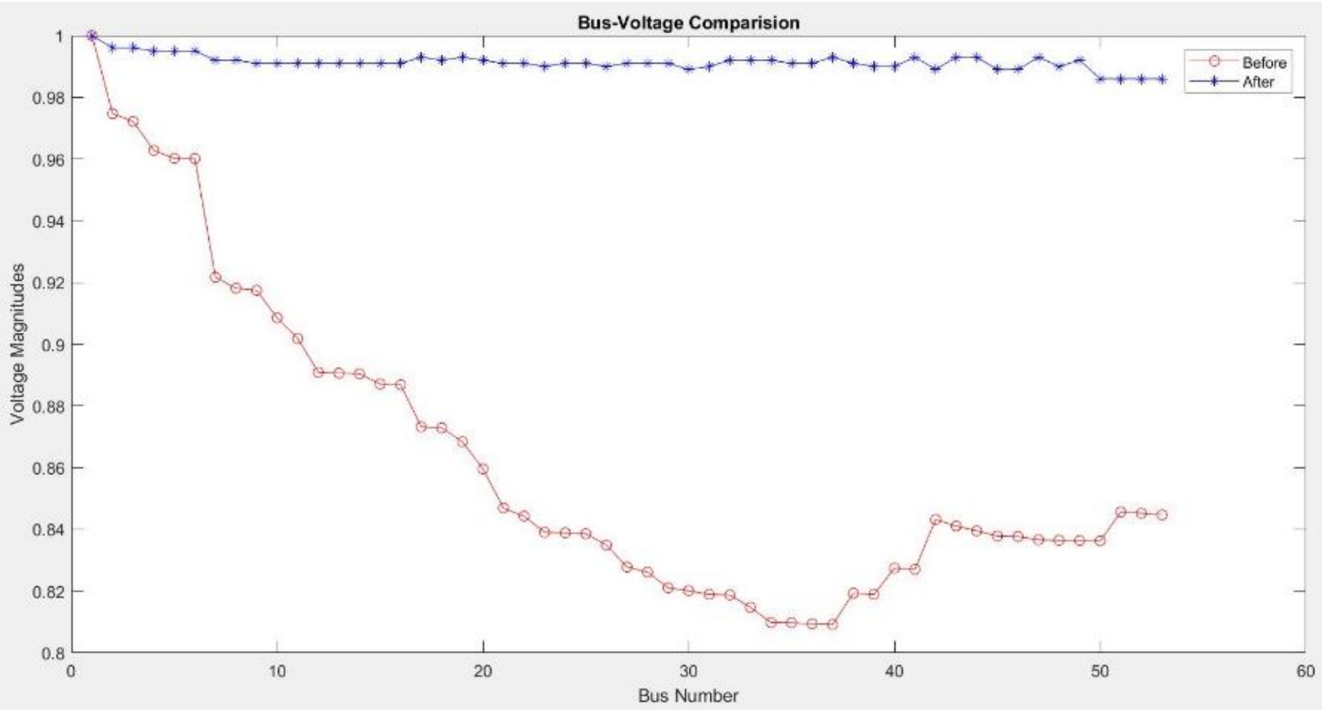

Figure 9. *Bus voltage comparison of Case III (Capacitors and DGs with unity pf simultaneously) for Sankhu feeder network.*

Figure 9 shows the combined output of capacitor and distributed generations. then the voltage magnitude of Sankhu feeder network improves from 0.82 to 0.99.

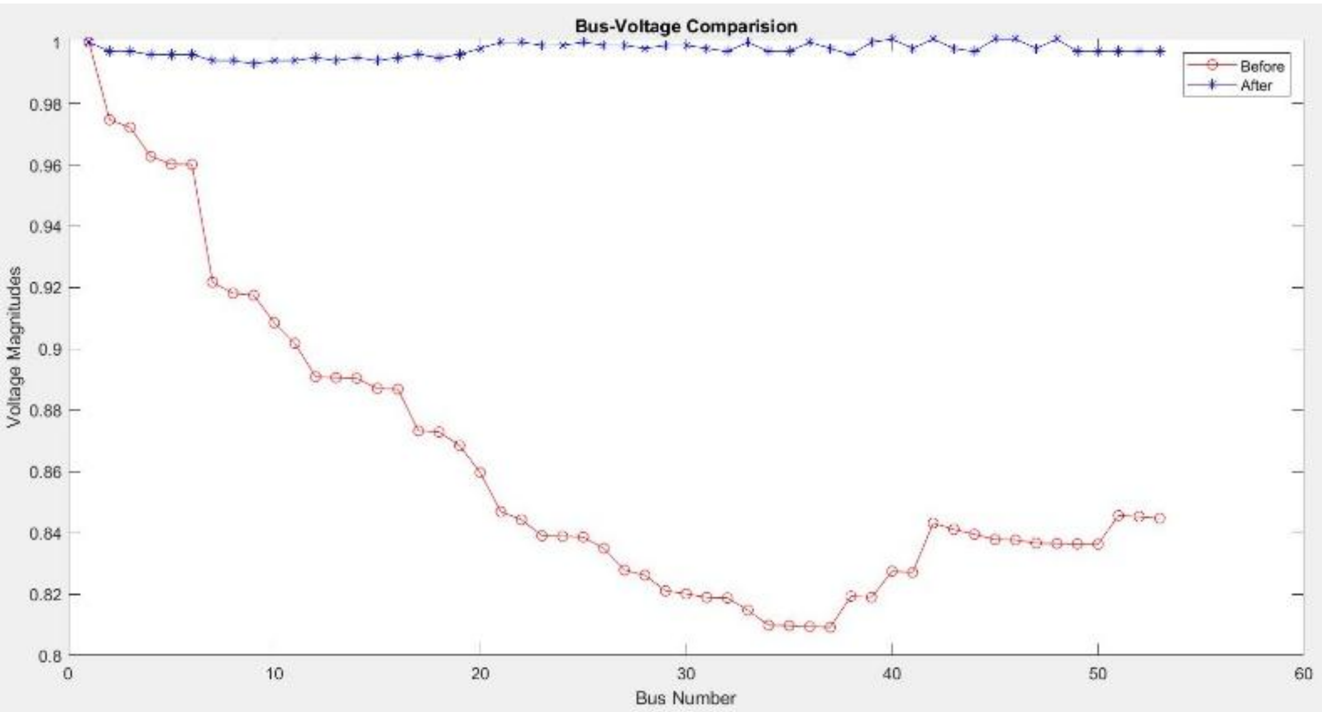

Figure 10. *Bus voltage comparison of Case IV (Capacitors and DGs with controllable pf simultaneously) for only technical objectives for Sankhu feeder network.*

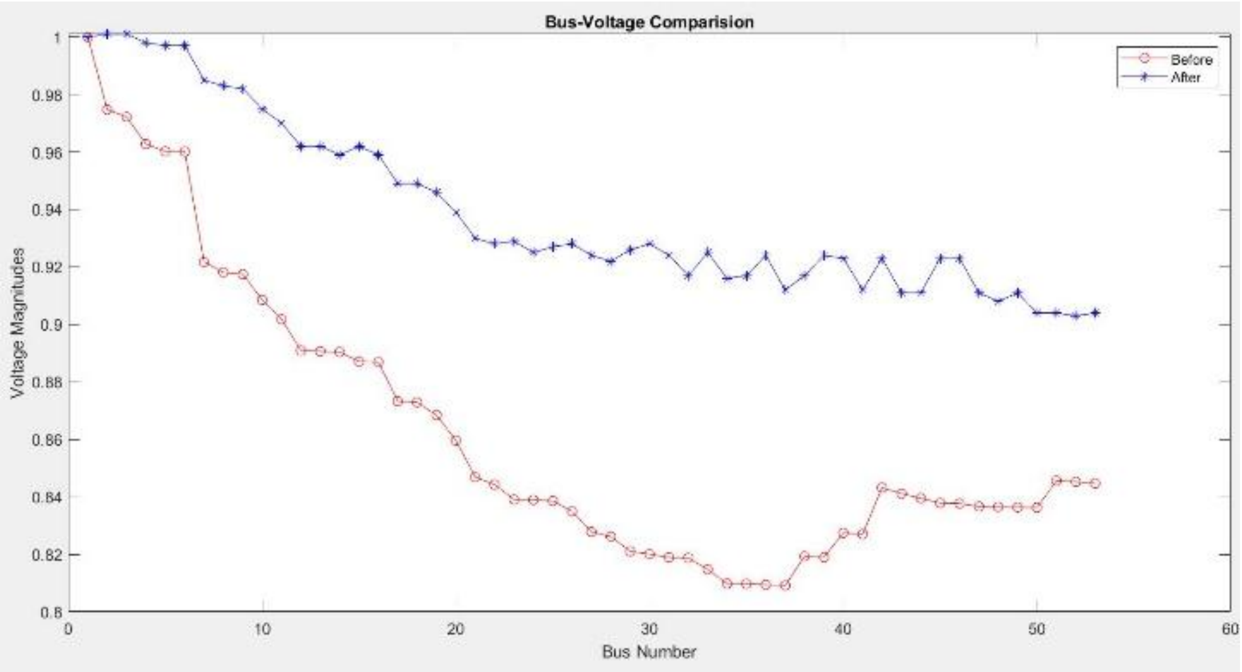

Figure 11. *Bus voltage comparison of Case V (Capacitors and DGs with controllable pf simultaneously) for techno- economic objectives for Sankhu feeder network.*

5. Conclusion

The optimal placement of capacitors and Distributed Generators (DGs) has been successfully achieved using the Water Cycle Algorithm (WCA), with results demonstrating a marked improvement over other widely-used optimization techniques such as Particle Swarm Optimization (PSO), Bacterial Foraging Optimization Algorithm (BFOA), Genetic Algorithm (GA), Gravitational Search Algorithm (GSA), Composite Voltage Stability Index (CVSI), and Direct Current Injection Algorithm (DICA), among others. The comparative analysis reveals that the WCA outperforms these methods across key performance metrics, including solution accuracy, convergence speed, and computational efficiency. The research highlights the Water Cycle Algorithm's superior capability to tackle complex optimization problems in power systems, particularly in enhancing network reliability and operational efficiency. This underscores WCA's potential as a preferred choice for real-world applications involving the optimal placement and sizing of capacitors and DGs, contributing to the advancement of smart grid technologies and the integration of renewable energy. Consequently, this study establishes WCA as a robust and reliable optimization tool, promising significant advancements in the field of power system optimization.

Abbreviations

CBs	Capacitor Banks
DG	Distributed Generation
EL	Energy Loss
IEEE 69-BTS	IEEE 69-Bus Test System
IM	Islanding Mode
PF	Power Factor
PL	Power Loss
PSOs	Power System Operators
SFN	Sankhu Feeder Network
TEEC	Total Electrical Energy Cost
TL	Transmission Line
VP	Voltage Profile
VSI	Voltage Stability Index
WCA	Water Cycle Algorithm

Author Contributions

Yam Krishna Poudel is the sole author. The author read and approved the final manuscript.

Conflicts of Interest

The author declares no conflicts of interest.

References

[1] Abdulnasser, G., Ali, A., & Mohamed, E. E. M. (2021). Optimal Planning of Distributed Generation and Capacitor Banks in Distribution Networks. *2021 22nd International Middle East Power Systems Conference (MEPCON)*, 619–624. https://doi.org/10.1109/MEPCON50283.2021.9686260

[2] Ali, A., Abbas, G., Keerio, M. U., Mirsaeidi, S., Alshahr, S., & Alshahir, A. (2023). Multi-Objective Optimal Siting and Sizing of Distributed Generators and Shunt Capacitors Considering the Effect of Voltage-Dependent Nonlinear Load Models. *IEEE Access*, *11*, 21465–21487. https://doi.org/10.1109/ACCESS.2023.3250760

[3] Alwash, S., Ibrahim, S., & Abed, A. M. (2022). Distribution System Reconfiguration with Soft Open Point for Power Loss Reduction in Distribution Systems Based on Hybrid Water Cycle Algorithm. *Energies*, *16*(1), 199. https://doi.org/10.3390/en16010199

[4] Ayadi, F., Colak, I., Garip, I., & Bulbul, H. I. (2020). Impacts of Renewable Energy Resources in Smart Grid. *2020 8th International Conference on Smart Grid (IcSmartGrid)*, 183–188. https://doi.org/10.1109/icSmartGrid49881.2020.9144695

[5] Dagade, N. R., Dagade, R. V., & Godha, N. R. (2023). Optimal allocation of PV based DG and capacitor in radial distribution network. *7th IET Smart Cities Symposium (SCS 2023)*, 632–636. https://doi.org/10.1049/icp.2024.1030

[6] Hajar Alimorad. (2024). Optimization of dynamic control systems using water cycle algorithm. *Journal of the Franklin Institute*, *361*(8), 106831–106831. https://doi.org/10.1016/j.jfranklin.2024.106831

[7] Ibrahim, S., Alwash, S., & Aldhahab, A. (2020). Optimal Network Reconfiguration and DG Integration in Power Distribution Systems Using Enhanced Water Cycle Algorithm. *International Journal of Intelligent Engineering and Systems*, *13*(1), 379–389. https://doi.org/10.22266/ijies2020.0229.35

[8] Judge, M. A., Khan, A., Manzoor, A., & Khattak, H. A. (2022). Overview of smart grid implementation: Frameworks, impact, performance and challenges. *Journal of Energy Storage*, *49*, 104056. https://doi.org/10.1016/j.est.2022.104056

[9] Mahato, J. P., Poudel, Y. K., Chapagain, M. R., & Mandal, R. K. (2024). Power Loss Minimization and Voltage Profile Improvement of Radial Distribution Network Through the Installation of Capacitor and Distributed Generation (DG). *Archives of Advanced Engineering Science*. https://doi.org/10.47852/bonviewAAES42022031

[10] Eskandar, H., Sadollah, A., Bahreininejad, A., & Hamdi, M. (2012). Water cycle algorithm – A novel metaheuristic optimization method for solving constrained engineering optimization problems. *Computers & Structures*, *110-111*, 151–166. https://doi.org/10.1016/j.compstruc.2012.07.010

[11] Poudel, Y. K., & Bhandari, P. (2023). Control of the BLDC Motor Using Ant Colony Optimization Algorithm for Tuning PID Parameters. *Archives of Advanced Engineering Science*. https://doi.org/10.47852/bonviewAAES32021184

[12] Poudel, Y. K., Kumar Pudasaini, R., Kandel, D. N., Maharjan, S., Bhandari, Y., & Yadav, J. K. (2024). HIGH-FREQUENCY TRANSFORMER DESIGN FOR SOLID STATE TRANSFORMERS IN ELECTRIC POWER DISTRIBUTION SYSTEMS: A NOVEL DESIGN METHODOLOGY. In *International Journal of Applied Engineering & Technology Copyrights @ Roman Science Publications Ins* (Vol. 6, Issue 1).

[13] Poudel, Y. K., Pudasaini, R. K., Kandel, A., & Karki, N. R. (2024). Battery, Super Capacitor Based Hybrid Energy Storage with PV for Islanded DC Microgrid. *Archives of Advanced Engineering Science*. https://doi.org/10.47852/bonviewAAES42021869

[14] Sambaiah, K. S. (2022). Renewable energy source allocation in electrical distribution system using water cycle algorithm. *Materials Today: Proceedings*, *58*, 20–26. https://doi.org/10.1016/j.matpr.2021.12.569

[15] Nihat Pamuk, & Uzun, U. E. (2024). Optimal Allocation of Distributed Generations and Capacitor Banks in Distribution Systems Using Arithmetic Optimization Algorithm. *Applied Sciences*, *14*(2), 831–831. https://doi.org/10.3390/app14020831

[16] Khaled Fettah *et al.* (2024) 'Optimal Allocation of Capacitor Banks and Distributed Generation: A Comparison of Recently Developed Metaheuristic Optimization Techniques on the Real Distribution Networks of ALG-AB-Hassi Sida, Algeria', *Sustainability*, 16(11), pp. 4419–4419. Available at: https://doi.org/10.3390/su16114419

[17] Chauhan, G. and Bangia, S. (2020) 'Technical Aspects of Grid Connected PV Array', *IOP Conference Series: Materials Science and Engineering*, 804, p. 012050. Available at: https://doi.org/10.1088/1757-899x/804/1/012050.

[18] Nasir, M., Sadollah, A., Choi, Y. H. *et al.* A comprehensive review on water cycle algorithm and its applications. *Neural Comput & Applic* 32, 17433–17488 (2020). https://doi.org/10.1007/s00521-020-05112-1

[19] Eskandar, H. *et al.* (2012) 'Water cycle algorithm – A novel metaheuristic optimization method for solving constrained engineering optimization problems', *Computers & Structures*, 110-111, pp. 151–166. Available at: https://doi.org/10.1016/j.compstruc.2012.07.010

[20] Sadollah, A. *et al.* (2016) 'Water cycle algorithm: A detailed standard code', *SoftwareX*, 5, pp. 37–43. Available at: https://doi.org/10.1016/j.softx.2016.03.001

[21] Javed, M. Y. *et al.* (2021) 'Water Cycle Algorithm (WCA): A New Technique to Harvest Maximum Power from PV', *Cybernetics and Systems*, 53(1), pp. 80–102. Available at: https://doi.org/10.1080/01969722.2021.2008683

[22] Sadollah, A., Eskandar, H., Bahreininejad, A. *et al.* Water cycle algorithm for solving multi-objective optimization problems. *Soft Comput* 19, 2587–2603 (2015). https://doi.org/10.1007/s00500-014-1424-4

Research Fields

Yam Krishna Poudel: Micro Grid, Machine Learning, Distributed Generation, Modern Control algorithm, Smart Grid