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POWER LOSS MINIMIZATION OF AN IEEE 33 BUS RADIAL DISTRIBUTION GRID USING SYSTEM RECONFIGURATION WITH GENETIC ALGORITHM

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Abstract

This study tackles the issue of active and reactive power losses by reconfiguring a radial distribution network and optimizing the placement and sizing of distributed generation (DG) units and capacitors to improve network reliability and voltage management. The reconfiguration process is intricate and nonlinear, requiring the identification of the optimal radial arrangement to meet these objectives. These goals are mathematically formulated and addressed using optimization algorithms. The study explored the combined use of DG and capacitors in the reconfiguration process, finding that this integrated approach yielded better results than using either component alone. The combination of DG and capacitors notably reduced power losses and enhanced voltage profiles, underscoring the effectiveness of their joint deployment in distribution systems. Simulations were conducted on a 33-bus system, and findings were analysed across various scenarios, comparing the system's performance before and after optimization. MATLAB and ETAP were employed to obtain the results.

Keywords: power loss, reconfiguration network, radial network, distribution system, distribution generator, capacitor, genetic algorithms (GA) and particle swarm optimization (PSO)

List of Symbols/Acronyms

Cap: Capacitor
c_1, c_1:factor weighting
DG: Distribution Generator
DG and Cap: Distribution Generator and Capacitor
$gbest_i$: global best particle
I_K : Current line
iter: number of iterations
$iter_{max}$: number of maximum iterations
P_K: Active power sending end
$P_{DG\,(K)}$: Active power in the distribution generator
$P_{L\,(K)}$: Active power in load
P_{K+1}: Active power receiving end
$pbest_i$: personal best particle
PU: Per Unit
Q_K: Reactive power sending end
Q_{K+1}: Reactive power receiving end
r_1, r_2 : arbitrary quantities between 0 and 1
R : resistance
$s_i{}^K$: Position of particle
$s_i{}^{K+1}$: The new position of a particle
$v_i{}^K$; particle velocity
$v_i{}^{K+1}$: new particle velocity
V_K: Voltage sending end
V_{K+1}: Voltage across the receiving end
w: weight function
w_{max}: initial weight equal (0.9)
w_{min}: initial weight equal (0.4)
X: reactance
Z: impedance

1. INTRODUCTION

Electrical distribution networks are vital components of the power system. In contrast to transmission networks, which are less complex and are connected via transformer stations, distribution networks are denser and more intricate [1]. These networks are responsible for significant power losses, ranging from 5–13% of total power generation and most customer interruptions, approximately 80% of total disruptions. Addressing these issues is crucial for ensuring high-quality electricity delivery to consumers [2-4]. Additionally, network reliability, defined as the continuous provision of sufficient quality electricity, is essential [5].

Several strategies have been proposed to minimize power loss and enhance voltage stability, aiming to achieve a flexible voltage control system, improve operational efficiency, and meet consumer demands while actively managing network operations. These strategies include network reconfiguration, distributed generation (DG) installation, capacitor placement, and energy storage system installation [6-9]. Network reconfiguration effectively reduces power loss and stabilizes voltage profiles, enhancing overall distribution system performance [10].

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Distribution systems are generally radial in design, simplifying coordination between feeder protection systems and reducing short-circuit currents. Each load point is connected to the substation via designated routes within the system components [11, 12]. Network reconfiguration involves adjusting the open/close status of sectionalizing and tie-line switches to modify the system's topology. This can improve system performance based on various objectives and constraints. Due to the nonlinear nature of distribution system constraints and the large number of switching elements, reconfiguring a distribution network presents a multi-objective, combinatorial challenge with inherent uncertainties. The complexity of the problem often renders exact optimization methods impractical, but heuristic techniques are well-suited for tackling the intricate optimization challenges of distribution system reconfiguration [13-15] Achieving optimal solutions necessitates careful consideration of several factors, including precise network modeling, timely management of topology changes, load flow calculations, formulating objective functions and constraints, and decision-making techniques for determining the optimal electrical configuration [16].This paper introduces efficient methods based on Genetic Algorithms (GA) that were used to select the optimal reconfiguration state by representing each possible solution as an individual in a population, evaluating each individual based on an objective function, selecting the best individuals, and applying crossover and mutation operations to produce a new generation of improved solutions. On the other hand, Particle Swarm Optimization (PSO) was used to determine the best location and size for Distributed Generation (DG) units and capacitors. PSO mimics the behaviour of a swarm in nature, where each particle moves through the solution space based on the best position and the best position discovered by the swarm, leading to a gradual improvement of solutions until reaching optimality [17].The algorithm's performance is demonstrated on a 33-bus system, confirming its effectiveness in optimizing distribution networks.

2. LOAD FLOW ANALYSIS

Load flow management is essential for the advancement of modern power systems. Load flow analysis is a critical and indispensable technique for addressing power system operation and planning challenges. This study examines the steady-state conditions of the electrical system to determine power, current, voltage, real power, and reactive power flow under various load scenarios. Whether for designing new projects or evaluating modifications to existing systems, a load flow study is vital to ensure that system voltages and currents remain within safe limits and to assess the need for additional equipment or services [18, 19]. While classical optimization methods have historically been utilized to solve the OPF problem, their highly nonlinear and multi-modal nature often results in multiple local optimal. Consequently, conventional optimization techniques reliant on derivatives and gradients may struggle to identify the global optimal. As a result, heuristic solution techniques or algorithms have been employed [20].

Figure 1. illustrates how active and reactive power flow between system components, based on the voltage, phase angles, and line characteristics.

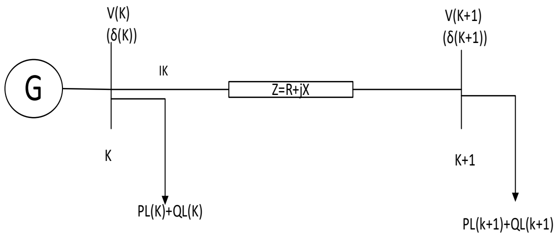

Fig. 1. Schematic diagram of power flow analysis

Mathematical equations representing active and reactive power [21].

$$V_{K+1} = V_K - I_K Z \tag{1}$$

$$|I_K| = \frac{\sqrt{P_K{}^2+Q_K{}^2}}{V_K} \tag{2}$$

$$P_{loss\,(K,K+1)} = \frac{P_{K+1}{}^2 + Q_{K+1}{}^2}{|V_{K+1}|^2} * R \tag{3}$$

$$Q_{loss\,(K,K+1)} = \frac{P_{K+1}{}^2 + Q_{K+1}{}^2}{|V_{K+1}|^2} * X \tag{4}$$

The primary aim of Optimal Power Flow (OPF) is to reduce system losses while optimizing voltage levels within the distribution system. This involves achieving the lowest possible voltage values with the least losses.

3. PROBLEM FORMULATION

3.1. Objective function

The objective function f(x) comprises two equations: the first aims to reduce active power losses, and the second aims to reduce reactive power losses while ensuring voltage parameters and other system constraints are maintained. The active and reactive power loss of the line is calculated from K, K+1

$$f(1) = P_{T\,loss} = \sum_{k=0}^{n} P_{loss\,(K,K+1)} \tag{5}$$

$$f(2) = Q_{T\,loss} = \sum_{k=0}^{n} Q_{loss\,(K,K+1)} \tag{6}$$

3.2. Constraints System

Constraints under which the network operates.

$$V^{min} \le V_{(K,K+1)} \le V^{max} \tag{7}$$

$$V^{min} = 0.95\ Pu \tag{8}$$

$$V^{max} = 1.1\ Pu \tag{9}$$

$$P^{min} \leq P_{Loss(K,K+1)} \leq P^{max} \tag{10}$$

$$Q^{min} \leq Q_{Loss(K,K+1)} \leq Q^{max} \tag{11}$$

$$\sum_{k=0}^{n} \mathrm{P}_{\mathrm{DG}\,(\mathrm{K})} = \sum_{k=0}^{n} \mathrm{P}_{\mathrm{loss}\,(\mathrm{K,K+1})} + \mathrm{P}_{\mathrm{L}\,(\mathrm{K})} \tag{12}$$

4. POWER FLOW OPTIMIZATION USING GENETIC ALGORITHM

GA is a form of evolutionary artificial intelligence widely applied as an optimization tool in various domains. It involves several key steps: encoding individuals (chromosomes), generating populations, evaluating fitness, implementing crossover and mutation, and selecting candidates [22].This algorithm is selected for its effectiveness in tackling both complex optimization problems. Its design makes it highly capable of delivering satisfactory solutions efficiently [23]. In this study, a genetic algorithm is utilized to address the reconfiguration of a distribution network; this is done by selecting the key states through which you will perform the network reconfiguration, as illustrated [24].

Five loops in the IEEE 33-bus distribution network are proposed in Table 1. Next, all possible permutations of these five loops are generated, resulting in 120 permutations.

Table 1. The loops of the IEEE 33-bus radial distribution system

No. of Loop	Relevant configuration of sectionalizing and tie branches
Loop 1	3, 4, 5, 22, 23, 24, 25, 26, 27, 28, 37
Loop 2	9, 10, 11, 12, 13, 14, 34
Loop 3	2, 3, 4, 5, 6, 7, 18, 19, 20, 33
Loop 4	6, 7, 8, 15, 16, 17, 25, 26, 27, 28, 29, 30, 31, 32, 34, 36
Loop 5	3, 4, 5, 22, 23, 24, 25, 26, 27, 28, 37

(a) Randomly select one permutation from the 120 generated permutations of the five loops.
(b) For the selected permutation, ensure each loop contains unique branches by removing branches in subsequent loops that appear in preceding loops. For example, if the permutation has loops ordered as 1, 2, 3, 4, and 5, branches in loop 1 are removed from loops 2, 3, 4, and 5, and branches in loop 2 are removed from loops 3, 4, and 5, and so on.
(c) The total number of random reconfigurations is 10,000 possibilities.

- Load the IEEE 33-bus radial distribution system.
- Close all sectionalizing and tie switches.
- Randomly open one branch from each of the five loops in the selected and modified permutation.
- Run load flow analysis. If voltage constraints are satisfied, calculate the total real power losses.
- If the power losses are the global best, record the optimal combination of opened branches that led to these power losses. If not, repeat the process to obtain the best value. The genetic algorithm determines the Global Best Value by evaluating all solutions across all generations. This is ensured by monitoring the algorithm's convergence and running it multiple times to guarantee reaching the best solution and avoiding local optimal.
- Print the total optimum real power losses and the best open branch combination.

The flow chart in Figure 2. explains the process.

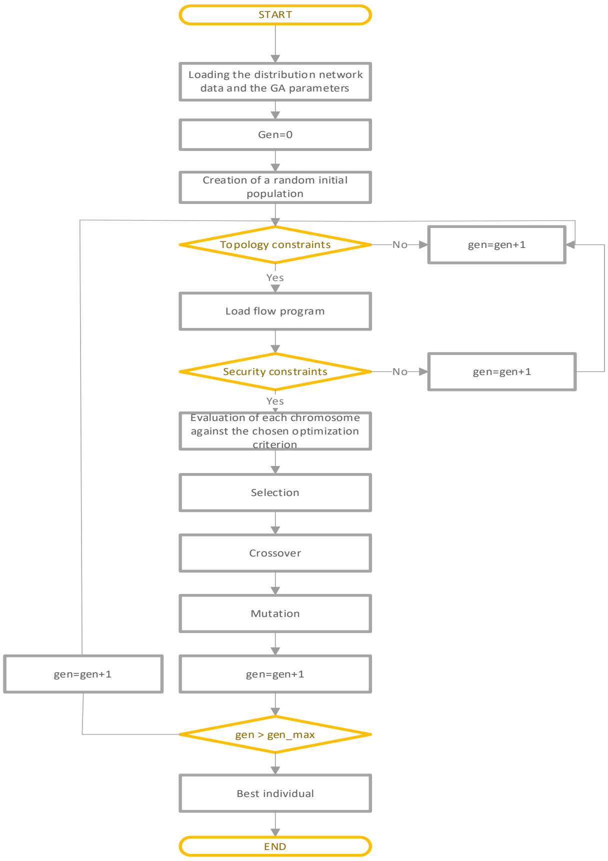

Fig. 2. DS reconfiguration with GA Process [25]

5. PARTICLE SWARM OPTIMIZATION

PSO is an optimization method inspired by the behaviour and intelligence of swarms. Developed in 1995, PSO utilizes social interaction principles to address complex problems. PSO models a system of individuals (particles) moving within a search space to find the optimal solution [26]. Each particle in the swarm is initialized with random velocities and tracks the best position it has achieved, known as 'pbest.' Additionally, PSO maintains the best overall position found by any particle in the swarm, referred to as 'gbest.' With each iteration, PSO updates the velocity and position of each particle. This update is influenced by random numbers that weigh the acceleration towards both pbest and gbest. The velocity is adjusted based on the previous velocity and the distances to pbest and gbest [27]. In essence, PSO involves updating the velocities of particles to move them toward their pbest and the gbest. Each particle modifies its current position and velocity based on its distance to both pbest and gbest. Upon finding better positions, particles update their velocities and positions accordingly. The velocity update for each particle is governed by a specific equation [28].

$$v_i^{K+1} = wv_i^K + c_1r_1(pbest_i - s_1^K) + c_2r_2(gbest_i - s_i^K) \quad (11)$$

$$s_i^{K+1} = s_i^K + v_i^{K+1} \quad (12)$$

$$\mathrm{w} = \mathrm{w}_{\max -} \frac{\mathrm{w}_{\max -}\mathrm{w}_{\min}}{\mathrm{iter}_{\max}} * \mathrm{iter} \quad (13)$$

The flow chart in Figure 3. explains the process [29].

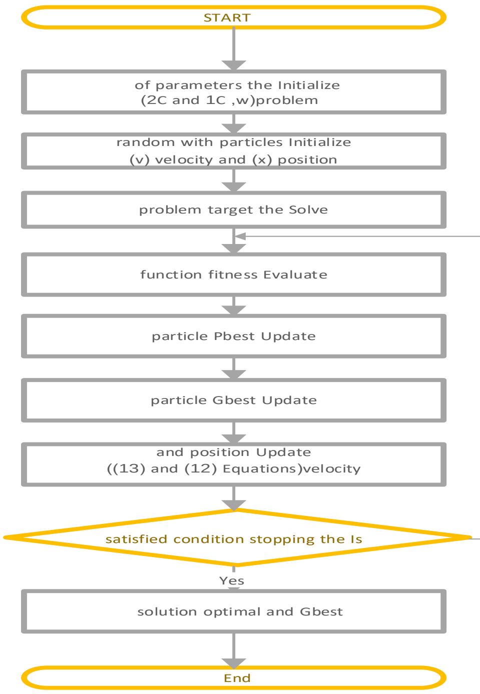

Fig. 3. Flow Chart PSO Process

6. TEST SYSTEM DESCRIPTION

A test system, a radial distribution system with a capacity of 12.66 kV and 100 MVA, was used for the method. The system comprises 33 buses, 5 connecting lines, and 37 branches. When all the branches are connected, we get 5 loops and the total real power losses are 197.6 kW [30], as shown in Figure 4.

7. CASE STUDY

This study performed a simulation to minimize losses by reconfiguring the network, selecting the optimal size and location for the distribution generator and the capacitor, and integrating both the distribution generator and the capacitor. The process involved the following steps:

- The IEEE 33-bus circuit was selected for analysis using the ETAP program.
- The optimal switches were identified, and the network was reconfigured using the genetic algorithm.
- The best location and size of the DG, considering only active power, were determined using the PSO algorithm.
- The optimal location and size of the capacitor were identified using the ETAP program.
- Both the capacitor and the DG were then placed together in the network.
- Finally, the results were compared to achieve the lowest possible network losses.

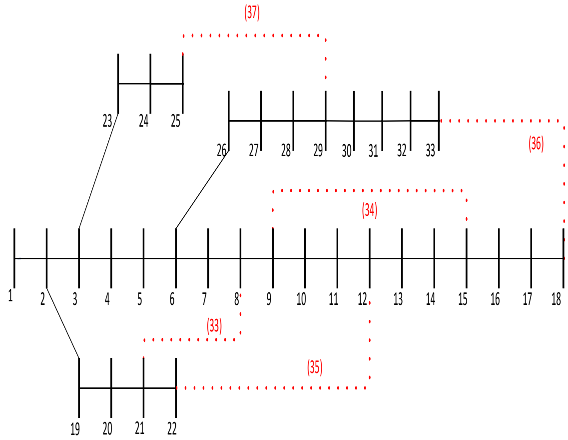

Fig. 4. Schematic diagram of the IEEE 33-bus system

8. SIMULATION RESULTS AND DISCUSSION

The proposed method was implemented using ETAP software for circuit analysis and MATLAB software for applying the algorithms to the proposed system. Most of the sources mentioned in this research focus on similar goals but do not use the DG and CAP methods. In our study, we applied this method and tried to combine the distribution and capacitance generator techniques. This approach yielded better results than using each method separately, surpassing the results of studies that applied each method separately. Nine cases were used to obtain the results, and the cases were compared to obtain the best solution.

Table (2) shows the results of active and reactive power losses for four scenarios: reconfiguration, distributed generation, capacitor, and distributed generation and capacitor. Reconfiguration significantly reduces active and reactive power losses. Distributed generation after reconfiguration reduces these losses even more, and capacitors help reduce both losses. The combination of distributed generation and capacitors leads to the largest reduction in active and reactive power losses. Therefore, for optimum performance, the reconfiguration should follow a basic step, followed by the combined use of DG and capacitors.

Table (3) details the locations and values of the distributed generators and capacitors in the electrical system. It includes columns for Location, indicating the location of each distributed generator or capacitor, and Type, which specifies whether the input is a distributed generator or capacitor, and the measured value in (kW) for distributed generators and (kvar) for capacitors.

Figure (5 to 31) illustrate the impact of each proposed solution method on voltage and both reactive and real power losses for each case.

The voltage graphs show the voltage on the vertical axis, measured per unit, and the number of buses on the horizontal axis, and each point represents the voltage value for each bus using the four methods. Higher voltage values indicate lower system losses, combining DG (Distributed Generation) and a capacitor, achieving the highest voltage and, therefore, the lowest losses.

For the power loss figures, the vertical axis represents power measured in (kW) for active power losses or (kvar) for reactive power losses. The horizontal axis indicates the number of transmission lines in the network, with each point displaying the power losses for each line. The method that combines DG with a capacitor demonstrates the best performance in minimizing losses.

All these figures pertain to individual circuit cases. Figure (32) and (33) present the real and reactive power losses across all nine cases, comparing the effectiveness of each method in different circuit scenarios.

Table 2. Comparison of Simulation Results of 33-Bus System

	Reconfiguration		With DG		With CAP		With DG and CAP	
Tie switch	P (kW)	Q (kvar)	P (kW)	Q (kvar)	P (kW)	Q (kvar)	P (kW)	Q (kvar)
,34,35,36,3733	257.07	174.02	155.16	108.46	149.56	100.37	66.78	48.79
33,9,34,28,36	159.49	144.17	108.79	90.24	123.74	125.03	69	70.91
9,14,32,37 ,7	155.95	127.2	95.65	78.73	74.72	62.61	75.26	63.23
14,28,7,17,8	162.51	153.04	139.27	129.83	103.17	92.41	80.52	69.78
31,7,9,14,37	164.32	128.25	156.26	122.75	113.53	88.22	98.33	77.67
7,10,14,28,32	148.17	145.24	140.71	140.17	97.28	90.64	94.83	91.07
14,16,9,7,27	167.28	158.26	120.77	138.6	101.18	92.29	55.58	64.33
7,9,14,28,32	147.94	146.51	109.05	129.04	95.81	91.92	57.95	74.97
7,8,14,37,32	177.43	141.29	116.41	84.78	114.82	92.91	57.67	39.8

Table 3. Placement and size of DG and Capacitors

Case	Case	1	2	3	4	5	6	7	8	9
DG	Placement	30	7	11	7	19	19	17	12	10
	Size kW	1311	1311	1311	1311	1311	1311	1311	1311	1311
Capacitors	Placement	16,27,30 32,33	16,31,32	18,31,32 33	31,32,33	7,15,30 33	17,22,33 31	17,18,21 24,31,32	12,17,27 31,32	4,9,13 14,26
	Size kvar	515,267 516,254 508	275,632 534	273,811 270,279	632,270 297	270,269 541,260	274,276 815,273	266,265 280,280 263,262	69.5,264 284,545 212	581,262 268,63.2 281
DG and Capacitors	Placement	30	7	11	7	19	19	17	12	10
	Size kW	1.311	1311	1311	1311	1311	1311	1311	1311	1311
	Placement	12,21,27 28,29,31	29,31	31,32	31,32,33	12,18,28 31	14,16,30 32	8,18,32	13,15,21 30,32	4,6,13 30,33
	Size kvar	268,296 560,560 273,279	279,274	271,814	271,212 270	547,263 277,545	274,267 549,270	282,1158 292	295,287 293,275 544	874,283 286,548 554

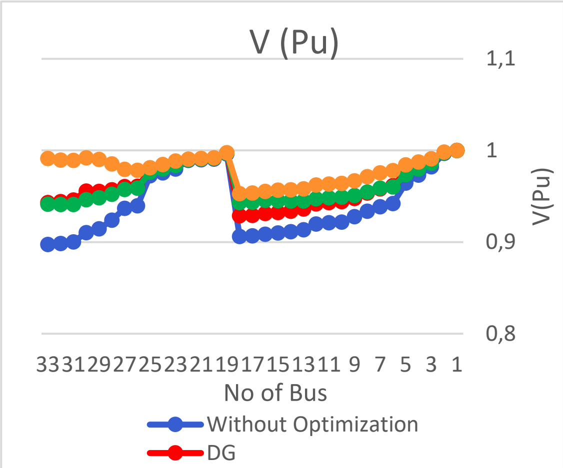

Fig. 5. Bus V

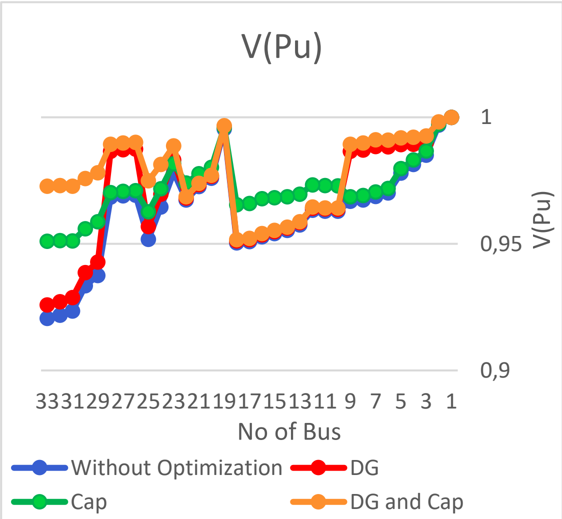

Fig. 6. Bus P loss (kW) case1

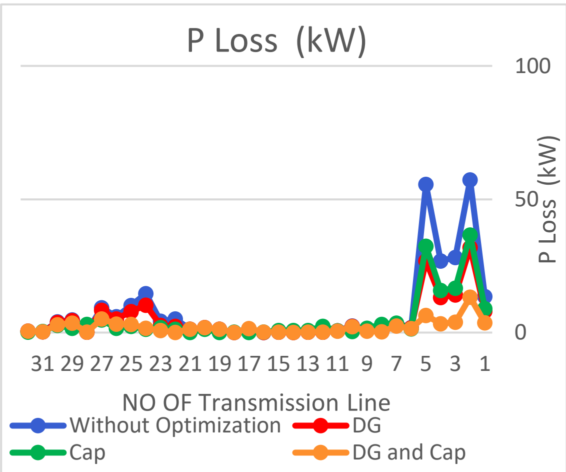

Fig. 7. Bus Q loss (kvar) case1

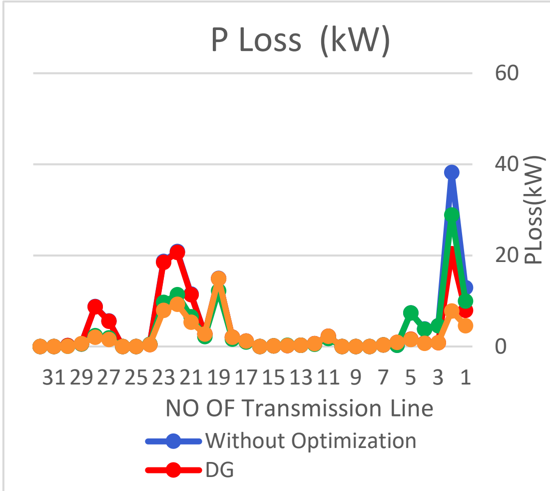

Fig. 8. Bus V case 2

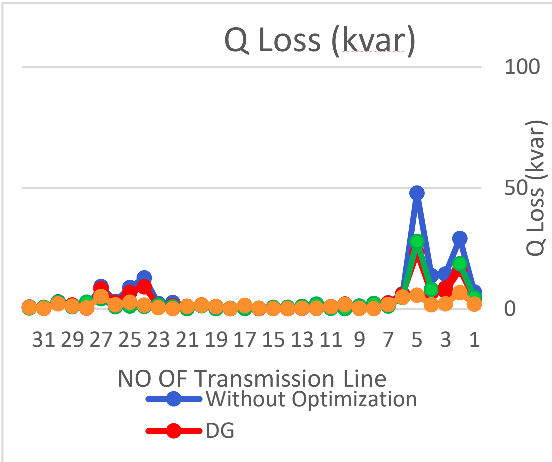

Fig.9. Bus P loss (kW) case2

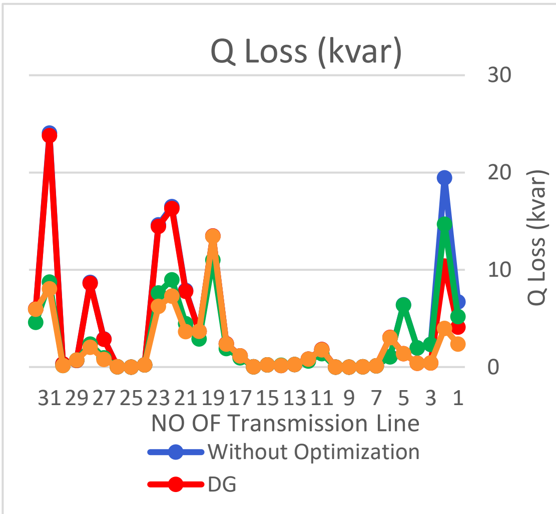

Fig. 10. Bus Q loss (kvar) case2

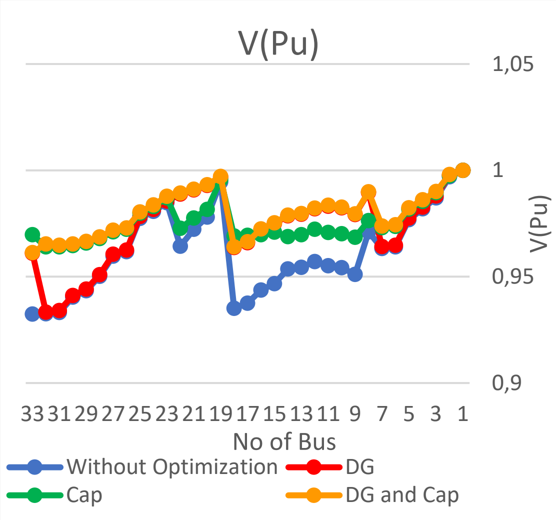

Fig. 11. Bus V case3

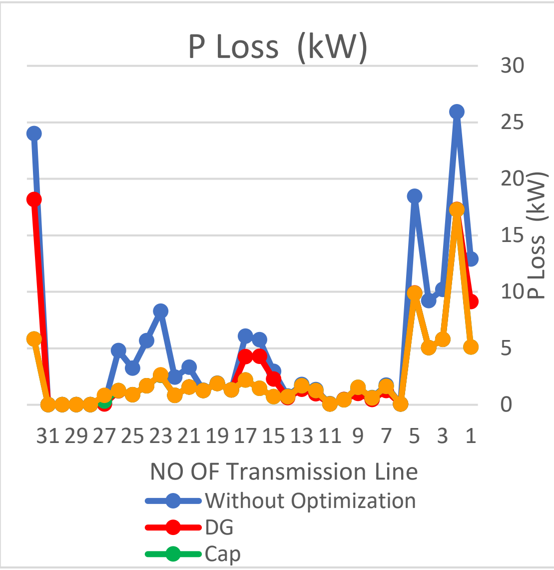

Fig. 12. Bus P loss (kW) case3

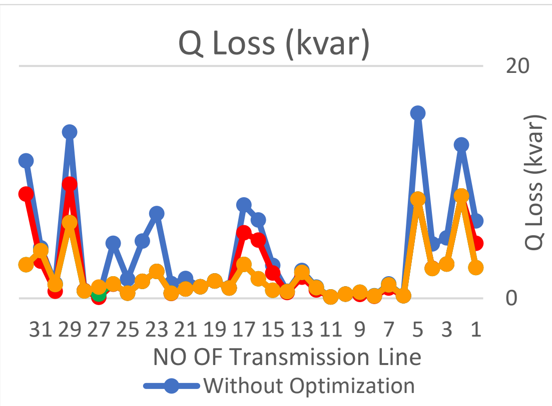

Fig. 13. Bus Q loss (kvar) case3

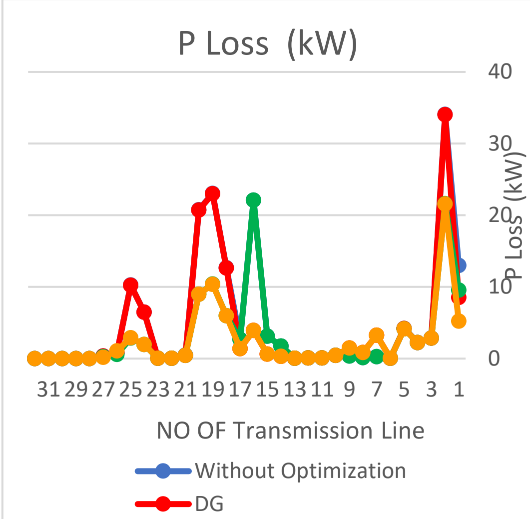

Fig. 14. Bus V case4

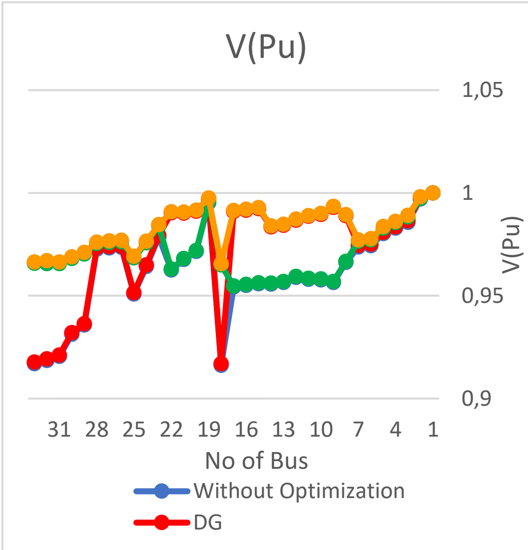

Fig. 15. Bus P loss (kW) case4

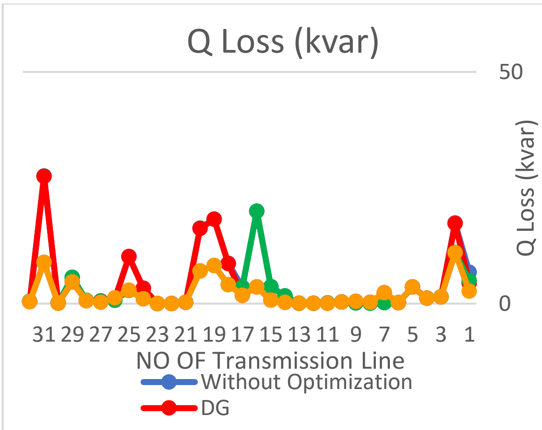

Fig. 16. Bus Q loss (kvar) case4

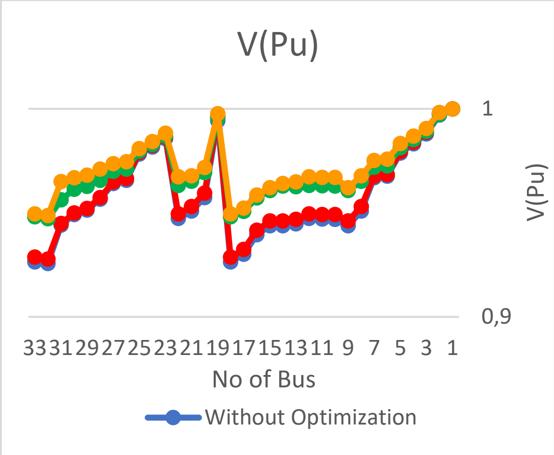

Fig. 17. Bus V case5

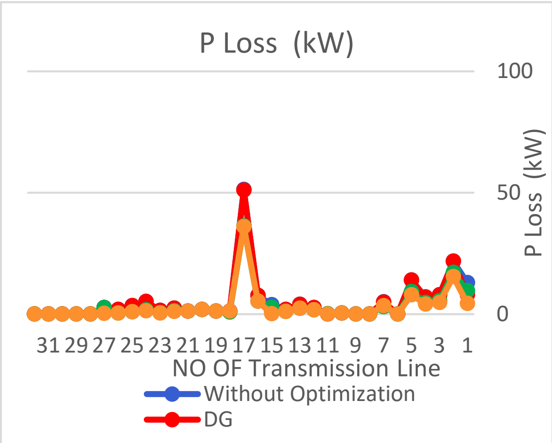

Fig. 18. Bus P loss (kW) case5

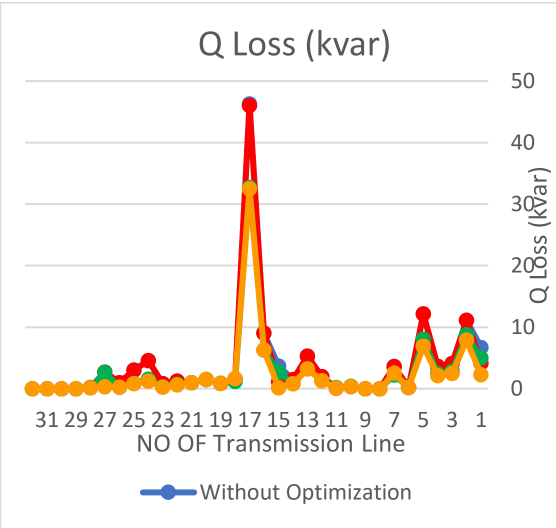

Fig. 19. Bus Q loss (kvar) case5

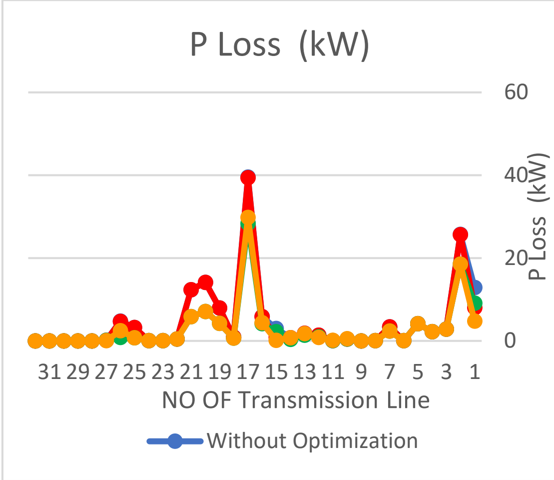

Fig. 20. Bus V case6

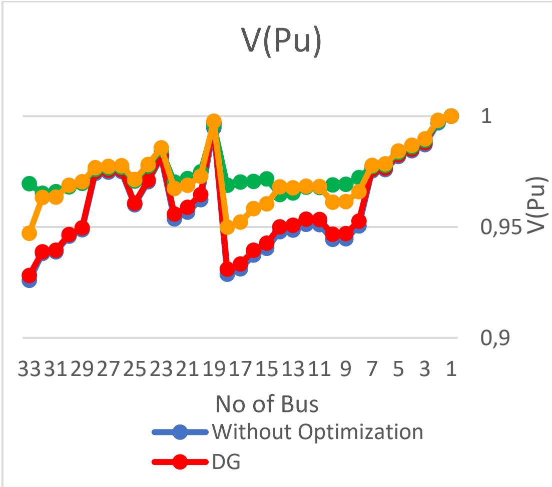

Fig. 21. Bus P loss (kW) case6

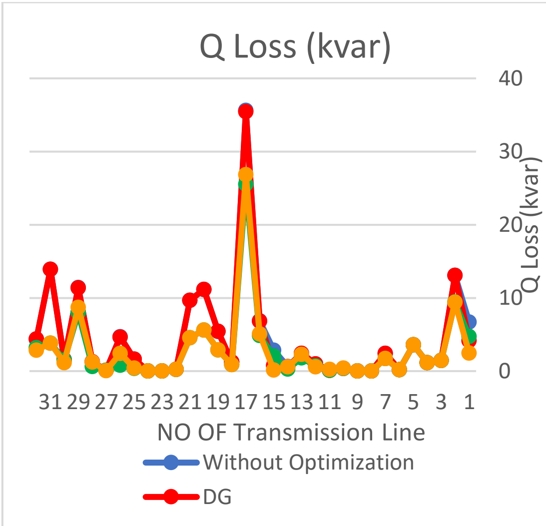

Fig. 22. Bus Q loss (kvar) case6

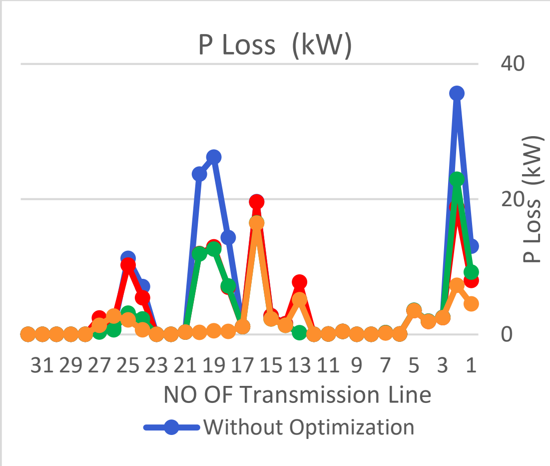

Fig. 23. Bus V case7

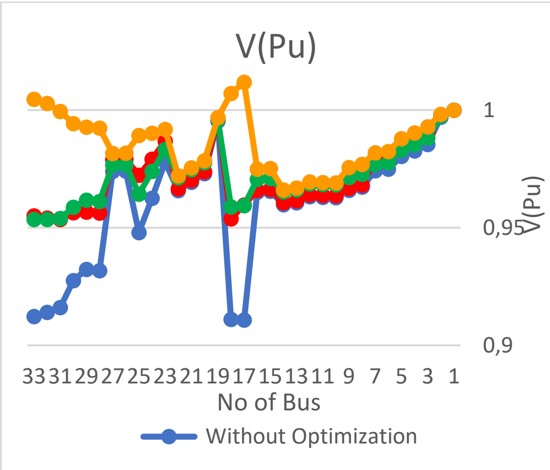

Fig. 24. Bus P loss (kW) case7

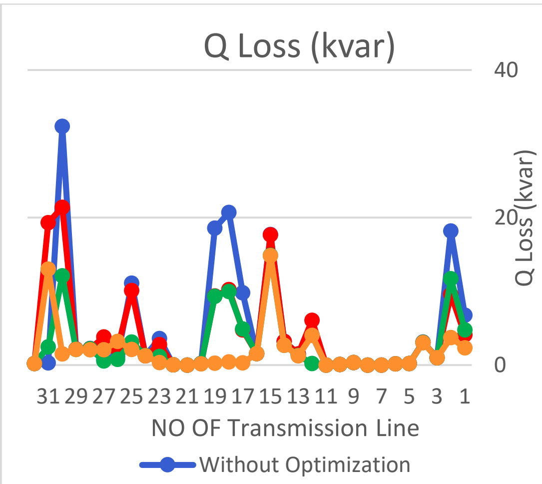

Fig. 25. Bus Q loss (kvar) case7

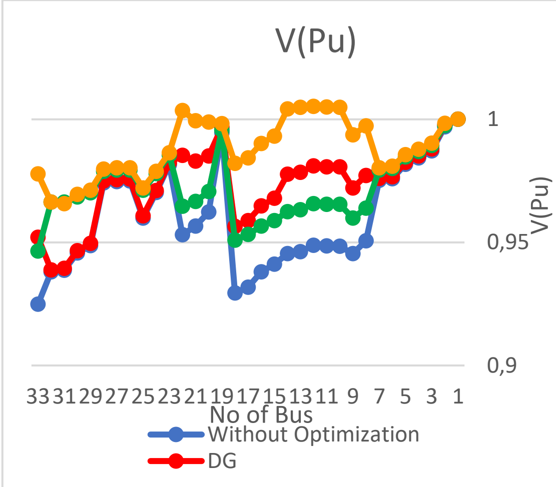

Fig. 26. Bus V case8

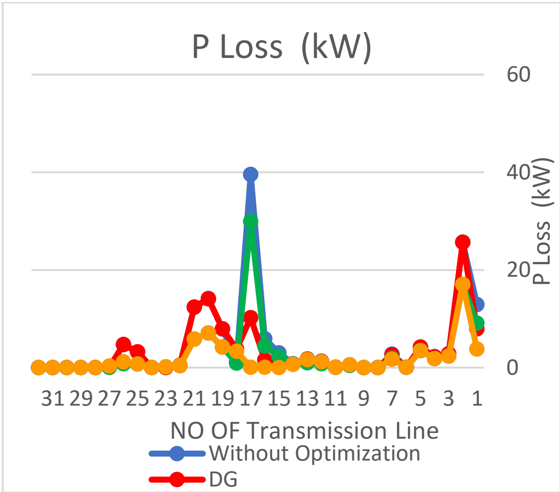

Fig. 27. Bus P loss (kW) case8

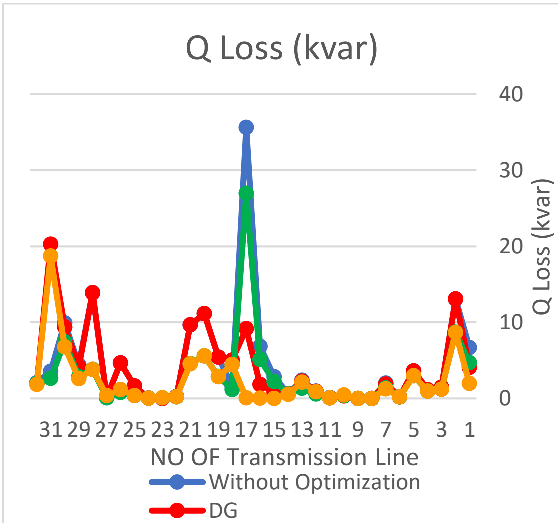

Fig. 28. Bus Q loss (kvar) case8

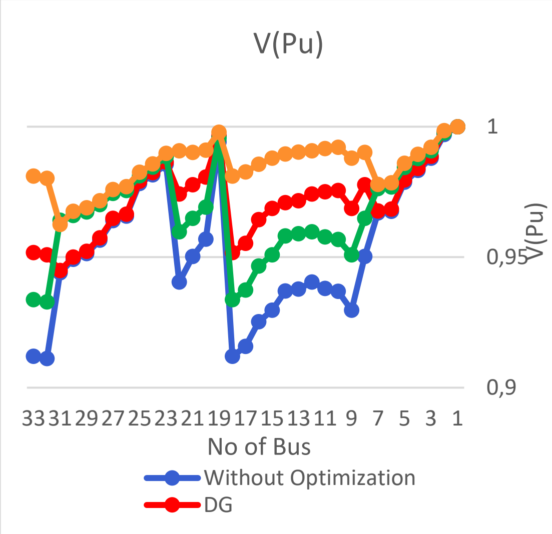

Fig. 29. Bus V case9

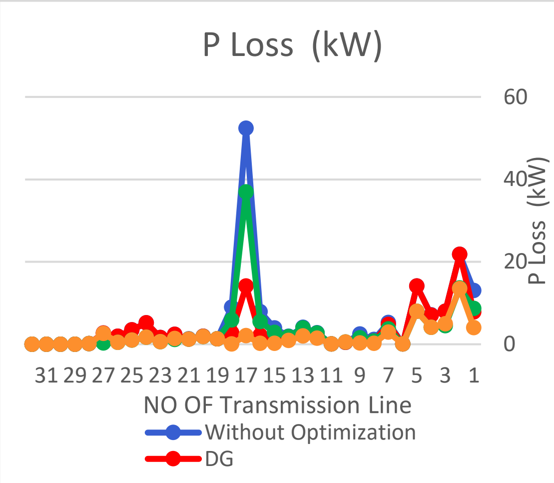

Fig. 30. Bus P loss (kW) case9

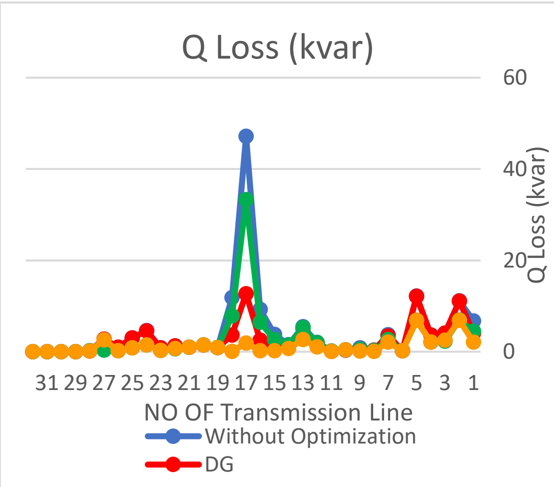

Fig. 31. Bus Q loss (kvar) case9

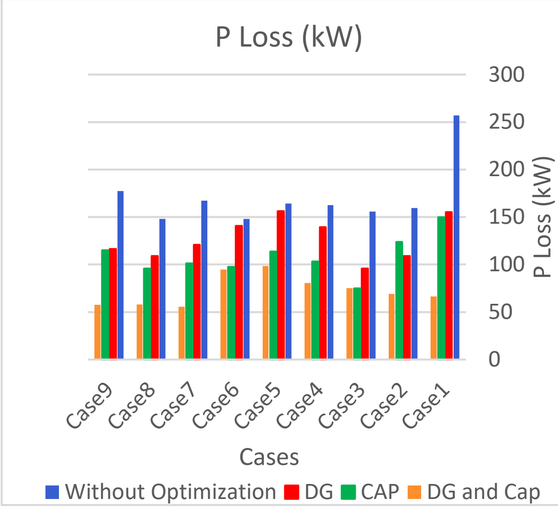

Fig. 32. the P loss values for all cases

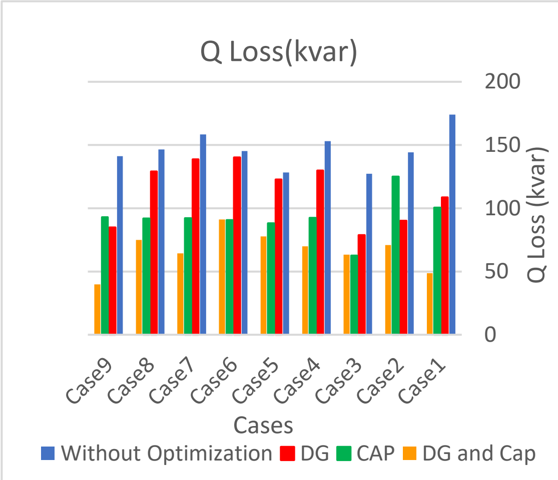

Fig. 33. the Q loss values for all cases

9. CONCLUSIONS

In this research, a combination of Genetic In this research, a combination of Genetic Algorithm (GA), Particle Swarm Optimization (PSO), and the ETAP and MATLAB programs were employed to reconfigure a radial distribution system and to determine the optimal location and size of DG and capacitors for a system consisting of 33 buses operating at 12.66 kV. The results were highly positive, successfully achieving the key objectives, including significant reductions in energy losses through efficient management of switch operations. The optimal strategy for minimizing losses was adding the DG and the capacitor simultaneously. Case 7 yielded the lowest active power losses, while Case 9 yielded the lowest reactive power losses. Furthermore, the voltage profile was improved, resulting in more stable voltage levels. These enhancements are clearly illustrated through th tables and diagrams presented in this study. Achieving these goals has significantly increased the reliability of the distribution system.

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