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Multi Objective Active and Reactive Power Optimization to Peak Shaving and Efficiency Improvement in Distribution Networks

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Abstract

The distribution system provides the relationship between the customer and transmission network. Research shows that in a three-part of power system including, generation, transmission and distribution, the highest percentage of losses is related to the distribution system. Recorded data also show that most interruptions in power provision to the customers is due to the cause of the malfunction in the distribution network. On the other hand, with the advent of smart grids in recent years the role of Distributed Generation (DG) in the electricity industry has been growing. There are a lot of control tools for active and reactive power management is network that with the right strategy can be utilized for costs reduction and improve in the power quality. The controllable variables in this study are power production of DGs, the amount of reactive power provided by capacitors and the distribution substation transformers tap, by which active and reactive power management in smart distribution network is performed. Due to the complexity associated with the distribution network and high number of optimization variables (capacitor steps in each capacitor bank, power production of DGs) in the thesis imperialist competitive algorithm is employed that using the control variables determine an appropriate control strategy during a day to minimize costs, losses while all network constraints such as the grid voltage are within a reasonable range. The proposed method is carried out on 69-bus standard distribution test system and the obtained results show that by optimal control of the controllable variables the desired goals could be achieved. The results also demonstrate the ability of the proposed method is finding the optimal solution.

۱- Introduction

In recent years, distribution networks have faced significant challenges due to the increasing number of subscribers and their consumption, especially during peak hours. During peak periods, many distribution system equipment operates at their maximum capacity. This not only increases the likelihood of incidents and reduces the lifespan of power system equipment but also deteriorates the quality of electricity supplied to customers. To address these challenges, distribution companies have tools at their disposal to improve network conditions. The most important of these tools is the control of active and reactive power. Available equipment for controlling active and reactive power includes distribution transformer taps, capacitor banks, and voltage regulators. Improving energy efficiency in distribution systems through voltage reduction has gained significant attention in recent years due to its numerous advantages. This approach is known as voltage reduction for savings. Reference [A1] attempts to control the active and reactive power of the network using distributed generation sources connected to the network through converters. The obtained results show that the proposed method in this reference has led to controlling the network voltage within an acceptable range. Although this reference proposes a new method in this regard that can be applied to very large networks, it does not consider other variables in the network such as capacitors and tap transformers, and also neglects other objectives such as reducing operating costs of the network. In reference [A2], a multi-objective method for controlling active and reactive power in the network in the presence of generation sources and FACTS devices has been proposed. Although in this reference, optimization goals have been partially achieved using FACTS devices, the performed optimization has not considered the costs of purchasing power from the network and distributed generation sources, and the simulation has only been performed for peak hours. In reference [A3], an active and reactive power control method using a fuzzy optimization approach has been proposed. Although the proposed method in this reference considers tap transformers and capacitors, it models the network without distributed generation sources. Given the importance of active and reactive power control and voltage reduction for savings in recent years, many studies have been conducted in this field. References [A4] have examined the effects and benefits of voltage reduction in distribution networks and have shown that by reducing consumer voltage within the allowable operating limits, the total power received from the upstream network can also be reduced. On the other hand, with the emergence of smart grids, active and reactive power control has become more and more feasible and its performance can be improved. The tools available for this purpose include tap transformers, voltage regulators, capacitor banks, and other distribution system operating tools [A5]. Additionally, by controlling the voltage of the low-voltage network, system efficiency can be increased [A6]. Reference [A7] has investigated active and reactive power control in the environment of smart grids. Despite many studies conducted in the field of distributed generation sources, there are fewer studies on the simultaneous installation of these sources and capacitors. In reference [A8], an analytical method for the simultaneous location and sizing of distributed generation sources and capacitors in distribution networks has been proposed. The optimization goal is considered to be loss reduction; in [A9] a similar goal has been investigated and the particle swarm algorithm has been used for optimization and better results have been obtained. In recent years, with the advancement of artificial intelligence algorithms in various management fields, especially in unpredictable environments, it seems that the use of such algorithms for resource management and increasing network reliability is inevitable. It should be noted that in these types of algorithms, due to the exploratory nature of the solutions, the solution time for complex and multi-variable problems is significantly reduced [A10].

Given the complexities associated with distribution networks and the existence of many optimization variables in this problem, simulating it using classical mathematical methods is very complex, and the use of an evolutionary method is proposed for optimization. The imperialist competitive algorithm, which is one of the newest and most powerful evolutionary methods and has been used to solve complex problems so far, is proposed as an optimization method. The imperialist competitive algorithm has been used to solve complex power system problems so far. The results obtained from implementing optimization problems using this algorithm indicate the high ability of this algorithm to find the optimal solution. Also, in comparison with other evolutionary algorithms, in many cases, the imperialist competitive algorithm has been able to find better solutions [A11] and [A12]. Reference proposed the imperialist competitive algorithm to solve the reactive power dispatch problem in the electricity market. The optimization goal is considered to be minimizing losses and the costs paid to reactive power suppliers. The simulation has been performed on a 30-bus system and the imperialist competitive algorithm results in better solutions compared to the genetic algorithm. While [A13] has used this algorithm to optimize the reactive power of the wind farm. Wind turbines consume reactive power to generate active power. Due to the uncertainty in wind turbine power generation, finding the optimal solution using classical methods is not possible. As a result, the imperialist competitive algorithm has been used for this purpose in the above study and the simulation results show the high ability of this algorithm to find the optimal solution. In recent years, extensive research has been conducted to develop various solutions for controlling active and reactive power in distribution networks. Additionally, the voltage reduction approach has gained significant attention as an effective method for reducing losses and improving network efficiency. However, studies that simultaneously investigate the integration of these two approaches and evaluate their impact on network performance are limited. Furthermore, most existing studies have focused on one or a few specific objectives, such as loss reduction or voltage profile improvement, and simultaneous optimization of multiple objectives has been rarely addressed. This research aims to design and implement an intelligent control strategy that utilizes the imperialist competitive algorithm to manage active and reactive power in smart distribution networks. By controlling the output of distributed generation sources, adjusting capacitors, and controlling the tap position of the distribution substation transformer, this strategy seeks to reduce costs, losses, and improve voltage profile throughout the day. [A16]To address the challenges associated with wind power integration, this paper analyzes the impact of distributed renewable energy on the voltage of the distribution network. Taking into account the fast control of photovoltaic inverters and the unique characteristics of photovoltaic arrays, we establish an active distribution network voltage reactive power-optimization model for planning the active distribution network. The model involves solving the original non-convex and non-linear power-flow-optimization problem. By introducing the second-order cone relaxation algorithm, we transform the model into a second-order cone programming model, making it easier to solve and yielding good results. The optimized parameters are then applied to the IEEE 33-node distribution system, where the phase angle of the node voltage is adjusted to optimize the reactive power of the entire power system, thereby demonstrating the effectiveness of utilizing a second-order cone programming algorithm for reactive power optimization in a comprehensive manner. Subsequently, active distribution network power quality control is implemented, resulting in a reduction in network loss from 0.41 MW to 0.02 MW. This reduces power loss rates, increases utilization efficiency by approximately 94%, optimizes power quality management, and ensures that users receive high-quality electrical energy. [A17]This paper explores the uncertainties of EV load sizes and the coordination of active and reactive power. A multi-objective optimization model was developed to augment the flexibility of the distribution network and mitigate the risk of load shedding. The Monte Carlo method is utilized to simulate scenarios with EV load uncertainties. To simplify the power flow calculations in the proposed convex optimization model, the Dataflow equation was adopted. Case study results demonstrate that managing EV loads in the distribution network can significantly reduce load shedding costs by 80 %, and the proposed EV charging strategy can effectively eliminate load shedding costs in most scenarios. [A18]In this method, a layered coordinated intelligent control model of source network load and storage is established. The upper model takes the minimum annual comprehensive cost as the coordination control goal and optimizes the installation capacity of distributed generation and energy storage systems in the candidate installation locations; the lower level model proposes a peak-shaving and valley-filling operation strategy for the energy storage system, which aims at minimizing the network loss to control the stable operation of the power system; using a dual-objective Pareto solution method based on a modified ε-constraint method, solve the upper and lower control models, obtain the Pareto optimal solution set of available schemes, and then use the fuzzy decision method to extract the optimal location and capacity scheme of distributed generation and energy storage systems that can ensure the stable operation of power systems. After testing, the annual investment cost and maintenance cost of DG and ESS decreased by 5,139,500 yuan and 0.024 yuan, respectively, after using this method; The fluctuation of load power in energy storage systems is significantly reduced. At the same time, the consumption of wind/photovoltaic power has increased from around 1800 MW h to around 3200 MW h, indicating a significant improvement in the consumption of new energy. It has higher economic efficiency and good peak-shaving and valley-filling effects. [A19] This review paper synthesizes the recent advancements in voltage regulation techniques for active distribution networks (ADNs), particularly in contexts with high renewable energy source (RES) penetration, using photovoltaics (PVs) as a highlighted example. It covers a comprehensive analysis of various innovative strategies and optimization algorithms aimed at mitigating voltage fluctuations, optimizing network performance, and integrating smart technologies like smart inverters and energy storage systems (ESSs). The review highlights key developments in decentralized control algorithms, multi-objective optimization techniques, and the integration of advanced technologies such as soft open points (SOPs) to enhance grid stability and efficiency. The paper categorizes these strategies into two main types: analytical methods and computational methods. In conclusion, this review underscores the critical need for advanced analytical and computational methods in the voltage regulation of ADNs with high renewable energy penetration levels, highlighting the potential for significant improvements in grid stability and efficiency. [A20]This paper proposes a multi-objective optimal operation strategy for VPP that considers the physical constraints of the distribution network, as well as a cost-benefit allocation approach for VPP and prosumers. On the basis of the distribution network, a VPP energy-sharing alliance is first constructed. Then, refined models of distributed energy resources such as PV, energy storage, electrical vehicles, and gas turbines in prosumers are established. Thirdly, a multi-objective optimization model is proposed that considers economic efficiency, distribution network losses, and peak-to-valley load disparity at the slack bus. Finally, a cost-benefit allocation method for VPP and prosumers based on the supply-demand ratio is proposed. The effectiveness of the strategy provided in the paper is validated using the IEEE33 node case study. The results indicate that compared to the non-optimization scenario, the VPP energy-sharing alliance can reduce prosumer operating costs by about 31.2 %, and decrease peak-to-valley load disparity of the distribution network by 30 %.

2- Objective Function and Constraints of the Problem

The first objective function of cost optimization is modeled as follows:

$$Min f_1 = \sum_{t=1}^{T} \left\{ \sum_{i=1}^{N_{sub}} (\text{Price}_i^t \times \text{P}_{sub,i}^t) + \sum_{i=1}^{N_{DG}} (\text{Price}_{\text{DG}_i}^t \times \text{P}_{\text{DG}_i}^t) \right\} \quad (١)$$

In the above equation, which we aim to minimize, Nsub and NDG represent the number of substations (power distribution companies) and the number of distributed generation units in the network, respectively. Additionally, $\text{Price}_{\text{DG}_i}^t$ and Price_i^t represent the price of power from the ith substation at time t and the price of power from the ith distributed generation unit at time t in the network, respectively. In this equation, $\text{P}_{sub,i}^t$ and $\text{P}_{\text{DG}_i}^t$ represent the power drawn from the ith substation at time t and the power generated by the ith distributed generation unit at time t in the network, respectively.

The second objective is to minimize the losses in the network."

$$Min f_2 = \sum_{t=1}^{Nd} \sum_{i=1}^{N_{br}} (R_i \times \left| I_i^t \right|^2 \times \Delta t) \quad (٢)$$

in which Δt is within one hour.

The third objective function is to improve the voltage profile, which is modeled as follows:

$$Min f_3 = \frac{\sum_{t=1}^{Nd} \sum_{i=1}^{N_{bus}} \left| \frac{V_i^t - V_i^*}{V_i^*} \right|}{Nd} \quad (٣)$$

Improving the voltage profile is considered as the third objective function. in which V_i^* is equal to one pu. This difference between node voltages is taken with nominal voltage.

The existing limitations for this problem are as follows:

Limitation of production capacity of distributed production unit:

$$P_{DG_i}^{Min} \le P_{DG_i} \le P_{DG_i}^{Max} \quad (٤)$$

In the above relationship, $P_{DG_i}^{Min}$ and $P_{DG_i}^{Min}$ represent the minimum and maximum power that can be extracted from the distributed generation unit, respectively.

Limitation of the power factor of distributed generation unit:

$$pf_{DG_i}^{Min} \le pf_{DG_i} \le pf_{DG_i}^{Max} \quad (٥)$$

In the above relationship, $pf_{DG_i}^{Min}$ $pf_{DG_i}^{Max}$ represent the minimum and maximum power factor of the distributed generation unit, respectively.

Limitation of transmission capacity of network feeders:"

$$(٦) kl=1,...,NL \left| T_{kl} \right| \le T_{kl}^{Max}$$

where the $\left| T_{kl} \right|$ is size of the power passing through the transmission line is kl and T_{kl}^{Max} is the maximum capacity of the power passing through the transmission line kl which connects buses k and l is, while NL is the number of lines in the network (between k and l buses, by changing these buses to all network buses, all network lines are covered.

Bus voltage limitation:

"In the above relationship, and represent the minimum and maximum power factor of the ith substation (if there is more than one substation), respectively. There is a limit on the minimum and maximum capacity of capacitor banks." (٧)

$$V_k^{Min} \le V_k \le V_k^{Max}$$

where and are respectively the minimum and maximum voltage limits of the bus k of the network.

Limitation of system tap transformers

$$Tap_i^{Min} \le Tap_i^t \le Tap_i^{Max} \quad (٨)$$

"In the above relationship, Tap_i^t represents the tap of the ith transformer at time t, and Tap_i^{Min} and Tap_i^{Max} are the minimum and maximum values of the ith transformer tap are 0.9 and 1.1, respectively.

Limitation of the number of tap changes per day:

The number of times the transformer tap can be changed per day is limited. In this study, the number of tap changes is considered to be 10.

Limitation of the maximum usable time of transformers per day:

$$DOT_i^{Trans} \leq MADOT_i^{Trans} \tag{٩}$$

"In the above relationship, DOT_i^{Trans} is the daily usage of the ith transformer, and $MADOT_i^{Trans}$ represents the maximum allowable usage time of the ith transformer.

Limitation on the maximum usable time of capacitors per day:

$$\sum_{t=1}^{T} U_{ci}^{t} \leq MADOT_i^{Cap} \quad i = 1,2,...,Nc \tag{١٠}$$

"In the above relationship, U_{ci}^{t} represents the usage of the ith capacitor at time t, and $MADOT_i^{Cap}$ represents the maximum allowable usage time of the ith capacitor. Also, Nc represents the total number of capacitors in the network.

Power factor limit at the substation:

$$pf_i^{Min} \leq pf_i \leq pf_i^{Max} \tag{١١}$$

"In the above relationship, pf_i^{Max} and pf_i^{Min} represent the minimum and maximum power factor of the ith substation (if there is more than one substation), respectively. There is a limit on the minimum and maximum capacity of capacitor banks."

$$Cap_i^{Min} \leq Cap_i \leq Cap_i^{Max} \tag{١٢}$$

In the aforementioned relationship, Cap_i^{Min} and Cap_i^{Max} represent the minimum and maximum capacities of the installed capacitors in the network, respectively.

In this research, the available data includes the power generation limits of distributed generation sources, bus voltage limits, feeder power limits, reactive power generation limits of capacitors, and information related to network buses for each hour of the day. The variables of this research include the amount of power generated by distributed generation sources, the amount of reactive power generated by network capacitors, and the tap of the distribution substation transformer. MATLAB simulation software is used to analyze the data. Given the presented modeling of the problem above, the large number of variables and constraints of the problem becomes apparent. Due to the complexities of this problem and the nonlinearity of the network model, optimizing this problem using classical mathematical methods is very time-consuming and, in some cases, impossible. Moreover, the probability of these methods getting stuck in local optima is very high. Therefore, in this research, the use of the colonial competitive algorithm is proposed for this purpose. The flowchart of this algorithm is as shown in Figure 1.

Backward-forward load flow optimization in radial networks

One of the new methods that has recently been proposed considering the radial structure of distribution networks is the use of the forward-backward method to solve the load flow problem. The general steps of this method are as follows: Backward sweep: Starting from the end buses and moving towards the slack bus, branch powers are calculated.

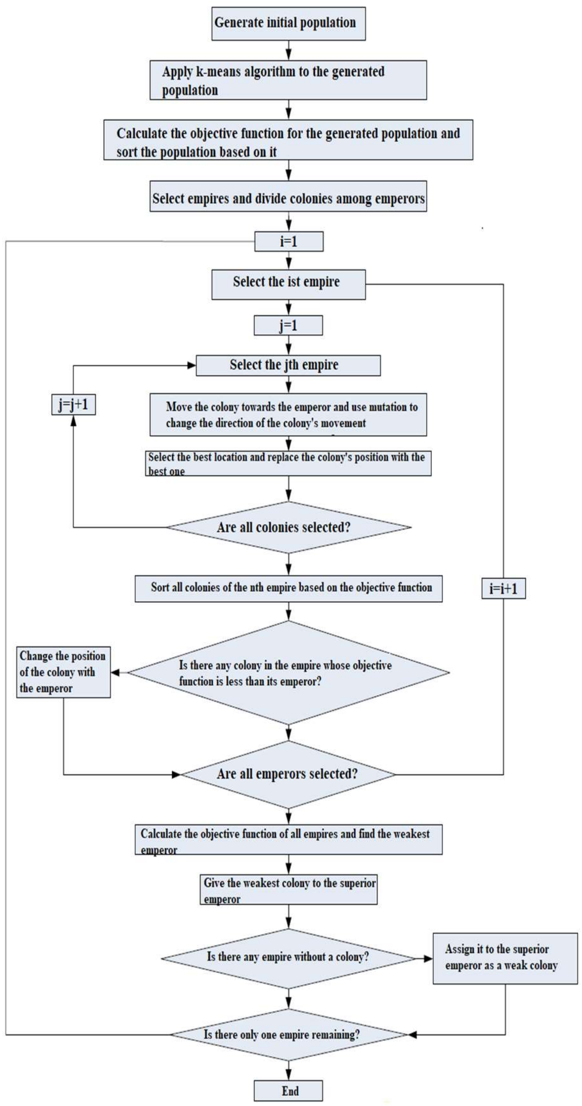


Figure 1- Flowchart of the proposed algorithm in the reference article

$$S_n = S_i + \sum_{m \in M} S_m + Loss_n \qquad (۱۳)$$

Sn: Power of branch n

i: Terminal node of branch n

Si: Injection into the load connected to node i

M: Set of branches connected to branch n at node i

Sm: Power of branch m

Loss n: Loss of branch n, assumed to be zero in the first iteration

Forward sweep: Starting from branches connected to the slack bus and moving towards the terminal branches, currents in the sending end bus of branch n, i.e., j, and voltages in the receiving end bus of branch n, i.e., i, are calculated.

$$J_n = \left(\frac{S_n}{V^j}\right)^* \qquad (14)$$

$$V^i = V^j - Z_n J_n \qquad (15)$$

Calculating branch losses:

$$Loss_n = (V^i - V^j) I_n^* \qquad (16)$$

Calculating voltage changes: After performing the above two steps in each iteration, the voltage mismatch for all buses is calculated:

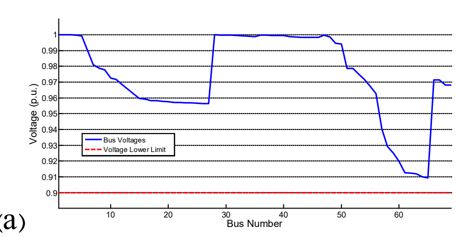
$$\Delta V^{i^{(k)}} = \left|V^{i^{(k)}}\right| - \left|V^{i^{(k-1)}}\right| \qquad (۱۷)$$

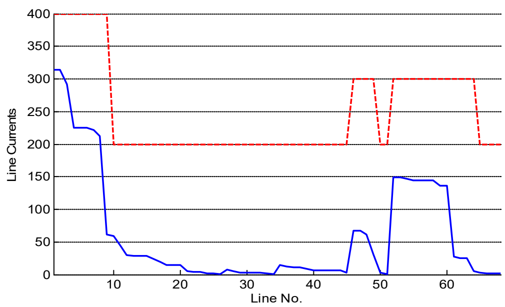
In these equations, k is the iteration counter. If any of the values exceeds the convergence criterion, steps (1) and (2) are repeated until convergence is achieved."

3- Results:

A 69-bus test network was used in the simulations. Information about this network can be extracted from references [A14] and [A15]. Initially, the network's base case conditions are examined. By performing a forward-backward load flow in this network at 100% load in the base case, the voltages of various buses and the amount of current in different lines are obtained according to Figure 2. The minimum allowable voltage limits and the maximum allowable current in these figures are shown in red as dashed lines. As seen in these figures, there is no problem from the point of view of the allowable current passing through the lines. Also, the amount of losses in this case is equal to 224.890."

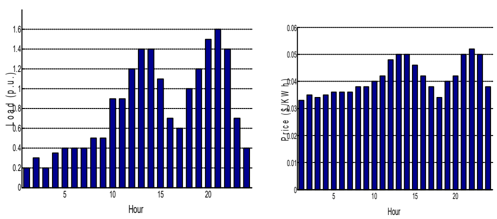
(a)





(b)

Figure 2: (a) Voltages of various buses in the 69-bus network under base conditions, (b) Currents of different lines in the 69-bus network under base conditions and the assumed current limits for each line. It is assumed that the transformer tap can adjust the reference bus voltage between 1.1 and 0.9 pu. The daily load profile and the price of power purchased from the substation are shown in Figure 3



(a) (b)

Figure 2: (a) Daily load variations, (b) Daily price variations.

Considering the provided information, the network is tested.

Initially, the network conditions under base case without distributed generation sources, transformer tap control, and capacitors are examined. Then, the presence of these elements is investigated. Table 1 presents the network characteristics including cost, losses, and minimum voltage of the network in each hour under the base case. As it can be seen, since the load exceeds 100% in some cases, the network voltage is less than 0.9 pu in some hours, indicating the need for network improvement and the use of distributed generation sources and capacitors. Bus 65, which is the farthest bus in the network, shows the minimum voltage at all times. Also, by observing the cost changes, it is clear that with the increase in load, the cost of purchasing electricity from the grid increases exponentially, as a result, the presence of distributed generation sources in those hours can significantly reduce the operating costs of the network.

Table 1: Network characteristics under base case

Minimum voltage (P.U)	Minimum voltage bass	losses (kW)	Cost ($)	hours
0.983146	۶۵	7.884017	31.03489	1
0.974511	۶۵	18.00621	49.60667	2
0.983146	۶۵	7.884017	31.97535	3
0.970139	۶۵	24.69579	58.01341	4
0.965728	۶۵	32.50552	68.36125	5
0.965728	۶۵	32.50552	68.36125	6
0.965728	۶۵	32.50552	68.36125	7
0.95679	۶۵	51.59559	90.64712	8
0.95679	۶۵	51.59559	90.64712	9
0.919291	۶۵	178.8679	175.4518	10
0.919291	۶۵	178.8679	184.2244	11
0.889009	۶۵	336.5095	285.7786	12
0.867565	۶۵	477.3082	351.8485	13
0.867565	۶۵	477.3082	351.8485	14
0.899336	۶۵	277.2971	249.5083	15
0.938409	۶۵	104.5023	141.7225	16
0.947686	۶۵	75.50988	109.3325	17
0.909425	۶۵	224.8909	166.6602	18
0.889009	۶۵	336.5095	238.1488	19
0.856404	۶۵	560.0453	318.8575	20
0.844917	۶۵	651.8966	407.8237	21
0.867565	۶۵	477.3082	365.9224	22
0.938409	۶۵	104.5023	168.7173	23
0.965728	۶۵	32.50552	72.1591	24
–	–	۴۷۵۳/۰۰۷	۴۱۴۵/۰۱۲	Total

3-1 Loss Reduction

Firstly, we examine the objective of reducing losses. In this case, the program manages the use of capacitors, distributed generation sources, and electricity purchased from the grid with the aim of minimizing network losses. By comparing the results obtained from Tables 1 and 2, it is clear that the optimal use of distributed generation sources, capacitors, and transformer taps can significantly reduce system losses and costs and improve the network voltage profile. The total cost in the base case is $4145, while in this case, the total cost has decreased to $4098, which is not very significant since the reduction in system operating costs was not the optimization target. The total losses in the base case are 4753 kWh, while in this case, the total losses have decreased to 1974 kWh, indicating a reduction of about 60% in system losses, which is very significant.

Table 2: Network characteristics under the program's operation with the aim of reducing losses

Minimum voltage (P.U)	Minimum voltage bass	losses (kW)	Cost ($)	hours

1.087516	27	0.871712	30.53	1
1.083629	61	2.667061	57.67	2
1.087917	27	0.860792	33.70	3
1.081993	61	4.087767	76.50	4
1.088959	61	6.032339	78.26	5
1.089554	61	5.896817	68.59	6
1.090199	61	6.221511	76.79	7
1.075138	61	11.56364	92.84	8
1.074998	61	11.41605	90.52	9
1.045923	64	64.28877	181.20	10
1.056356	64	63.02831	192.85	11
1.031357	64	141.3516	271.95	12
1.013998	64	218.9568	326.96	13
1.013998	64	218.9568	326.96	14
1.039824	64	111.0181	241.89	15
1.071981	62	30.24419	146.81	16
1.079231	61	19.15684	119.91	17
1.048155	64	84.95364	189.10	18
1.031357	64	141.4008	241.19	19
1.005082	64	263.4552	315.31	20
0.996	64	313.184	376.84	21
1.013998	64	218.9568	335.06	22
1.071969	62	30.25558	165.03	23
1.08004	61	6.166952	61.93	24
–	–	۱۹۷۴/۹۹۲۲	۴۰۹۸/۴۰۳	Total

Additionally, the usage pattern of capacitors and distributed generation over a 24-hour period demonstrates that their utilization is minimal during the early hours when electricity prices are low and the network load is light. However, maximum utilization of these two sources is observed during peak load hours (hours 13 and 14). Based on this usage pattern, it can be concluded that the proposed method has successfully managed the available resources in the network and minimized network losses. Table 3 presents the optimal transformer tap positions over a 24-hour period. As can be observed, in order to reduce losses, the colonial competitive algorithm has kept the transformer tap at a high level at all times. It is worth noting that in this case, cost is not a priority, and the sole objective is to minimize losses. As a result, the optimization program has increased the voltage at the system buses, reducing the current in the network lines and consequently decreasing system losses.

Table 3: Optimal transformer tap positions over a 24-hour period

hours	1	2	3	4	5	6
transformer tap	1.09	1.09	1.09	1.09	1.10	1.10
hours	13	14	15	16	17	18
transformer tap	1.10	1.10	1.10	1.10	1.10	1.10
hours	7	8	9	10	11	12
transformer tap	1.10	1.09	1.09	1.09	1.10	1.10
hours	19	20	21	22	23	24
transformer tap	1.10	1.10	1.10	1.10	1.10	1.09

3-2 Cost Reduction

In this scenario, the program manages the utilization of capacitors, distributed generation sources, and electricity purchased from the grid with the aim of minimizing the operating costs of the network. By comparing the results obtained from Table 4 and Table 1, it is evident that the optimal utilization of distributed generation sources, capacitors, and transformer taps can effectively reduce system costs and improve the network voltage profile. The total cost in the base case is $4145, while in this case, the total cost has decreased to $3606, indicating a significant reduction of approximately 10% in system operating costs. The total losses in the base case are 4753 kWh, while in this case, the total losses have decreased to 2329 kWh, representing a reduction of about 50% in system losses, which is quite remarkable.

Table 4: Network characteristics under the program's operation with the aim of reducing costs

Minimum voltage (P.U)	Minimum voltage bass	losses (kW)	Cost ($)	hours
1.08	65	4.94	25.33	1
1.08	65	10.46	40.34	2
1.08	65	5.32	26.11	3
1.08	65	14.23	47.10	4
1.06	65	20.07	55.48	5
1.07	65	19.00	55.44	6
1.07	65	18.81	55.43	7
1.06	65	31.60	73.43	8
1.06	65	31.29	73.42	9
1.03	64	104.84	143.00	10
1.03	64	96.17	149.71	11
1.02	64	150.32	240.45	12
1.01	64	218.96	326.96	13
1.01	64	218.96	326.96	14
1.02	64	138.83	206.16	15
1.05	62	47.28	113.12	16
1.05	64	42.84	88.44	17
1.02	65	142.72	137.71	18
1.02	64	157.13	208.99	19
1.01	64	263.46	315.31	20
1.00	64	313.18	376.84	21
1.01	64	218.96	335.06	22
1.05	62	39.69	126.95	23
1.06	65	20.85	58.59	24
–	–	۲۳۲۹/۸۹۹	۳۶۰۶/۳۰۲	Total

The results of the 24-hour analysis of distributed generation (DG) and capacitor utilization revealed that during the early hours when electricity prices are low and the network load is light, DG sources were not utilized due to their higher operational costs. However, the maximum utilization of these sources was observed during peak load hours (hours 13 and 14). This strategic deployment indicates that the proposed method effectively managed the available network resources

and minimized operating costs.
Table 5 presents the optimal transformer tap positions over a 24-hour period. As observed, to reduce costs, the colonial competitive algorithm consistently maintained a high transformer tap setting throughout the day. By increasing the voltage at the system buses, the optimization program reduced the current flow in the network lines, consequently decreasing system losses. The reduction in losses directly translated into a lower demand for power in each hour, leading to reduced overall costs.

Table 5: Optimal transformer tap positions over a 24-hour period

hours	1	2	3	4	5	6
transformer tap	1.09	1.10	1.09	1.10	1.09	1.10
hours	13	14	15	16	17	18
transformer tap	1.10	1.10	1.09	1.09	1.09	1.09
hours	7	8	9	10	11	12
transformer tap	1.10	1.09	1.09	1.09	1.09	1.09
hours	19	20	21	22	23	24
transformer tap	1.09	1.10	1.10	1.10	1.09	1.09

3-3 Voltage Profile Improvement

In this section, we delve into the objective of enhancing the voltage profile. In this scenario, the program manages the utilization of capacitors, distributed generation sources, and electricity purchased from the grid with the aim of optimizing the network voltage.By comparing the results obtained from Table 6 and Table 21, it is evident that the optimal utilization of distributed generation sources, capacitors, and transformer taps can effectively reduce system costs and improve the network voltage profile. The total cost in the base case is $4145, while in this case, the total cost has decreased to $3606, indicating a significant reduction of approximately 10% in system operating costs. The total losses in the base case are 4753 kWh, while in this case, the total losses have decreased to 2329 kWh, representing a reduction of about 50% in system losses, which is quite remarkable. The primary objective of optimization in this case, namely improving the voltage profile, is clearly evident in the results obtained for the network voltage. In this case, all voltages have converged to approximately 1 per unit. Comparing this to the previous two cases, it can be observed that by changing the objective function in this case, operating costs and losses have increased, indicating the correct functioning of the proposed method.

Table 6: Network characteristics under the program's operation with the aim of improving the voltage profile

Minimum voltage (P.U)	Minimum voltage bass	losses (kW)	Cost ($)	hours
0.999	61	5.02	50.80	1
0.998	50	7.50	62.59	2
0.999	50	8.24	49.54	3
0.996	61	8.98	92.17	4
0.993	61	10.94	97.76	5
0.993	61	11.72	82.41	6
0.993	61	10.01	105.45	7
0.986	61	14.65	96.42	8
0.986	61	17.59	112.72	9
0.962	64	76.06	172.91	10
0.962	64	76.08	182.83	11
0.975	64	170.46	264.91	12
1.014	64	218.96	326.96	13
1.014	64	218.96	326.96	14
0.944	64	134.86	234.92	15
0.977	62	43.81	158.30	16
0.978	61	25.26	131.93	17
0.953	64	102.83	169.70	18
0.975	64	169.92	225.74	19
1.005	64	263.46	315.31	20
0.996	64	313.18	376.84	21
1.014	64	218.96	335.06	22
0.977	62	43.74	161.76	23
0.993	61	10.43	72.56	24
–	–	۲۱۸۱/۶۱۱	۴۲۰۶/۵۱۷	Total

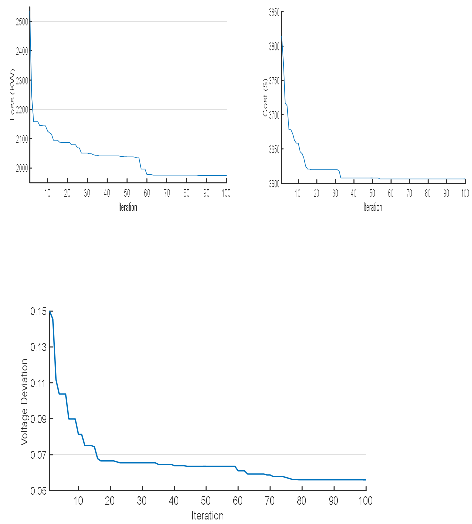
Additionally, the utilization of distributed generation sources and capacitors over a 24-hour period demonstrated that these resources were continuously used to maintain the network voltage as close to the per unit value as possible. Considering the utilization pattern of these two sources, it is evident that the proposed method effectively managed the available network resources and optimized the network voltage profile. Table 7 presents the optimal transformer tap positions over a 24-hour period. As observed, to regulate the voltage profile, the colonial competitive algorithm maintained the transformer tap close to 1 per unit throughout the day. During the early hours with light loads, the transformer tap was set to 1 per unit. As the network load increased, the transformer tap was increased, and during peak load hours (hours 13 and 14), the transformer tap was set to 1.1 per unit to prevent voltage sag. The obtained results demonstrate the high capability and accuracy of the algorithm in finding the optimal solution.

Table 7: Optimal transformer tap positions over a 24-hour period

hours	1	2	3	4	5	6
transformer tap	1.00	1.00	1.00	1.00	1.00	1.00
hours	13	14	15	16	17	18
transformer tap	1.10	1.10	1.01	1.01	1.00	1.01
hours	7	8	9	10	11	12
transformer tap	1.00	1.00	1.00	1.01	1.01	1.05
hours	19	20	21	22	23	24
transformer tap	1.05	1.10	1.10	1.10	1.01	1.00

4-Comparison of Results

In this section, we compare the results obtained under different scenarios. Figure 3 illustrates the convergence of results in terms of reducing losses, costs, and improving the voltage profile. Table 8 presents the simulation results



(a)(b)

(c)

a) Convergence with the objective of minimizing losses.
b) Convergence with the objective of minimizing costs.
c) Convergence with the objective of improving

"The results presented in Table 8 indicate a high level of simulation accuracy.

The significant 87% reduction in costs, which is also clearly shown in Figure 4, is a testament to the success of the cost reduction strategy."

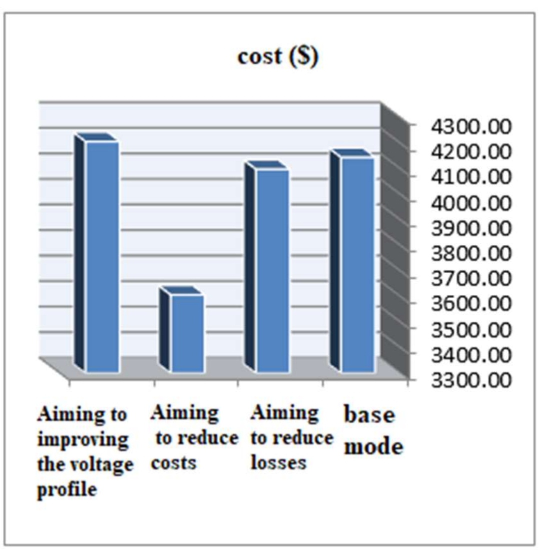


Figure 4 compares costs under different conditions. As shown in Figure 5, losses were reduced in all cases, with the most significant decrease observed when the primary goal was to minimize losses."

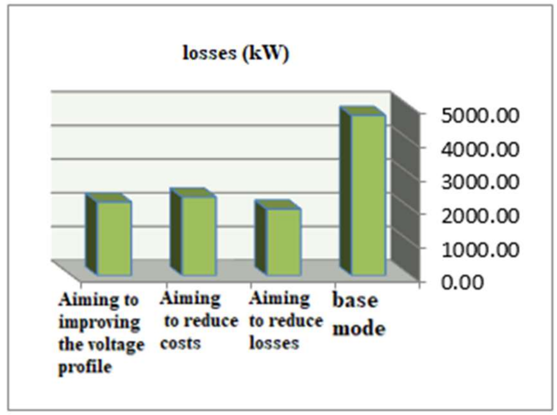


Figure 5: Comparison of Losses Under Different Conditions

To improve the voltage profile		To reduce costs		To reduce casualties		Base mode	
losses (kW)	Cost ($)	losses (kW)	Cost ($)	losses (kW)	Cost ($)	losses (kW)	Cost ($)
5.02	50.80	4.94	25.33	0.87	30.53	7.88	31.03
7.50	62.59	10.46	40.34	2.67	57.67	18.01	49.61
8.24	49.54	5.32	26.11	0.86	33.70	7.88	31.98
8.98	92.17	14.23	47.10	4.09	76.50	24.70	58.01
10.94	97.76	20.07	55.48	6.03	78.26	32.51	68.36
11.72	82.41	19.00	55.44	5.90	68.59	32.51	68.36
10.01	105.45	18.81	55.43	6.22	76.79	32.51	68.36
14.65	96.42	31.60	73.43	11.56	92.84	51.60	90.65
17.59	112.72	31.29	73.42	11.42	90.52	51.60	90.65
76.06	172.91	104.8	143.0	64.29	181.2	178.8	175.4
76.08	182.83	96.17	149.7	63.03	192.8	178.8	184.2
170.4	264.91	150.3	240.4	141.3	271.9	336.5	285.7
218.9	326.96	218.9	326.9	218.9	326.9	477.3	351.8
218.9	326.96	218.9	326.9	218.9	326.9	477.3	351.8
134.8	234.92	138.8	206.1	111.0	241.8	277.3	249.5
43.81	158.30	47.28	113.1	30.24	146.8	104.5	141.7
25.26	131.93	42.84	88.44	19.16	119.9	75.51	109.3
102.8	169.70	142.7	137.7	84.95	189.1	224.8	166.6
169.9	225.74	157.1	208.9	141.4	241.1	336.5	238.1
263.4	315.31	263.4	315.3	263.4	315.3	560.0	318.8
313.1	376.84	313.1	376.8	313.1	376.8	651.9	407.8
218.9	335.06	218.9	335.0	218.9	335.0	477.3	365.9
43.74	161.76	39.69	126.9	30.26	165.0	104.5	168.7
10.43	72.56	20.85	58.59	6.17	61.93	32.51	72.16
2181	4206.55	2329	3606	1974	4098	4753	4145

5. Conclusion

By utilizing control tools for managing active and reactive power, and adopting an appropriate strategy, it is possible to reduce costs and improve the power quality for customers. In this study, controllable variables such as the power output of distributed generation sources, the reactive power generation of network capacitors, and the tap of the distribution substation transformer were considered. By using these variables, active and reactive power in the smart distribution network were managed in a way that optimizes the desired objectives. The considered objectives include minimizing network operating costs, minimizing losses, and improving the network voltage profile. A colonial competitive algorithm was used for optimization. The results obtained from implementing the proposed method on a standard 69-bus test network showed that by optimally controlling the controllable variables, the desired objectives could be well achieved. In the case of minimizing losses as the objective function, the obtained results were very significant, such that network losses were reduced by about 50% compared to the base case of the network. In the case of reducing operating costs, the proposed algorithm also performed well, reducing operating costs over 24 hours by about 10%, which is a very significant amount in the long term. In the case of improving the voltage profile, the network, by controlling the distributed generation sources and capacitors, as well as optimally using the transformer tap, brought the bus voltages of the network closer to the reference voltage (1 per unit). The obtained results indicate the high ability of the proposed method in finding the optimal solution, and in all cases and with different objectives, it was able to optimize the target well by managing the resources. It is also worth mentioning that in power systems, reconfiguration is performed using existing switches to reduce losses and restore service. Considering reconfiguration in the optimizations performed is suggested for the continuation of this research.

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