Optimizing distribution system performance: A comprehensive review of power loss minimization techniques

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ABSTRACT

This article presents a thorough examination of contemporary techniques aimed at minimizing losses in distribution networks by strategically allocating capacitors, distributed generators (DG), and distribution static synchronous compensators (DSTATCOM). Through an extensive review of background literature and the analysis of current methodologies, the study distills insights from research articles spanning four decades. The survey encompasses diverse single and multi-objective methods, considering various constraints in addressing the distribution system loss minimization problem. Key findings emphasize the effectiveness of capacitor allocation in high voltage distribution networks, the efficiency of DG allocation in integrating small-scale generation, and the growing interest in DSTATCOM allocation for its advantages over traditional capacitor allocation. Particular attention is given to simultaneous techniques, identified as the most efficient approach for enhancing overall system performance.

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1. INTRODUCTION

The electrical grid is a sophisticated system that ensures the supply of electricity all the way to the end-users. Main components in the composition include power plants, transmission and distribution lines, transformers, and electric meters [1]. The electrical grid is usually divided into three levels: high voltage, medium voltage, and low voltage [2]. These levels are designed to carry the energy produced at production sites to end consumers in order to ensure maximum robustness, optimal efficiency, and improvement in the safety of electrical installations. Losses in the transmission and distribution network constitute a major problem in any power system. Increasing demand for electricity, a competitive energy market, and environmental concerns have led to the operation of transmission and distribution systems mostly under overloaded conditions, thereby making losses in the distribution system a major cause for concern. Essential conditions for acceptable power quality and increased efficiency must be met if the economic advantages are to be fully realized [3]. This has therefore provided an excellent environment for investigating loss minimization techniques and implementing modern operating practices [4].

The total power received by the distribution system depends on the difference between total power generation and transmission power losses [5]. Minimizing power losses is the only alternative to improve the efficiency of the distribution system. Thus, much research interest has been focused on the areas of distribution system loss minimization and voltage stability for the last few decades [6]. Several techniques have been proposed in the literature for power loss minimization.

Power losses in electrical systems should be at their minimum to bring forth better overall efficiency. Some of the techniques employed to minimize power losses include the following:
- Optimal system operation: The employment of advanced algorithms for the optimum scheduling and dispatch of power generation sources to minimize losses within the system.
- Load shedding and demand response: Intelligent load shedding during peak demand periods and the use of demand response programs for balancing load and reducing losses.
- Voltage regulation: Voltage regulation practices to maintain voltage within specified limits, allowing for a reduction in resistive losses.
- Power factor improvement: Installation of power factor correction devices to improve the power factor and reduce reactive power losses.
- Energy storage systems: Integrating energy storage systems to store excess energy during periods of low demand and release it during peak demand, smoothing out fluctuations and minimizing losses.
- High-efficiency transformers: This involves upgrading transformers to higher efficiency models with the view to reducing transformer losses.
- Distributed generation: Integrating dispersed generation, including renewable sources of energy, would help cut the losses in transmission and distribution by producing power near the consumers.
- Smart grid technologies: Implement smart grid technologies with real-time monitoring and control for better management of energy flows.
- Loss-aware routing in distribution systems: The smart routing algorithms will facilitate the best use of electrical power distribution, thus resulting in minimal loss in the distribution network.
- Fault detection and maintenance: This includes periodic fault detection in the power system, which comprises timely maintenance to avoid inefficiency and loss.
- Dynamic line rating: Dynamic line rating systems that adjust the carrying capacity of transmission lines depending on real-time weather and operational conditions.
- Transmission line design efficiency: Transmission lines shall be designed to optimize conductor size, insulation, and routing for minimum resistive losses.
- Advanced metering and monitoring: Advanced metering infrastructure installation will be accompanied by monitoring systems capable of detecting losses and inefficiencies in real-time.
- Predictive analytics: Predictive analytics, which makes it possible to forecast the conditions leading to the power losses and take proactive steps towards preventing them.
- Energy-efficiency components: Installation of energy efficiency devices and elements in the power system, such as efficient motors and transformers.

The combination of the mentioned techniques, considering the specific characteristics of the power system, can remarkably contribute to power loss minimization and significantly improve the overall efficiency of the system [7].

2. METHOD

2.1. Approaches for planning and operating involve methodologies for network reconfiguration

The approaches have been adopted for the planning and operation of distribution networks have been several. The section provides different techniques on methodologies of network reconfiguration, capacitor allocation, distributed generation (DG), and distribution static synchronous compensator (DSTATCOM) for the planning and operation of distribution systems.

2.2. Capacitor allocation

Capacitor allocation refers to the strategic placement and optimization of capacitors within an electrical power system. This process involves determining the most effective locations for installing capacitors in order to enhance power factor correction, improve voltage regulation, and reduce overall power losses. The goal of capacitor allocation is to optimize the distribution of capacitive reactive power in the network, leading to improved energy efficiency and enhanced system performance.

Capacitor allocation is the strategy of placing capacitors at selected points in the power distribution system to achieve:
- Power factor correction: Improve power factor by canceling out inductive loads, which would subsequently reduce reactive power demand and improve the efficiency of the overall system.
- Voltage regulation: Stabilize the voltage levels in a way that maintains them within acceptable limits without causing voltage fluctuations.

- Loss minimization: Reduce resistive losses in distribution to a negligible level by lowering the flow in reactive power, thence optimizing and improving power-factor.
- Capacity release: This will optimize the use of existing infrastructure by freeing up transmission and distribution system capacity, enabling increased load-carrying capacity.
- Energy conservation: Save energy by increasing efficiency in the transmission and distribution of electricity, thereby reducing energy losses.

The allocation of capacitors in a network has to be a very critical analysis due to the characteristics of load, power factor requirements, and configurations of the system. Advanced optimization algorithms coupled with simulation tools can be used in the identification of optimum locations for the installation of capacitors by considering the dynamics of the power systems. Therefore, capacitor allocation is an extremely important aspect of power system planning and optimization, which fails in improving the general efficiency, reliability, and performance of the distribution network. The evolution of techniques for capacitor allocation is presented in Table 1.

Table 1. Evolution in capacitor allocation techniques

Author, year [ref]	Optimization approaches	Objective(s) type	Basic principle/ objective function	Network
El-Fergany, 2013 [8]	Differential evolution and pattern search (DE-PS)	Line active energy losses minimization	$min\ f = min(PT, Loss)$	34-bus and 69-bus test radial distribution system
Ramadan *et al.*, 2014 [9]	Fuzzy-based approach	Voltage profile, power loss, and cost	$minCost = Cp \times PTloss + J$ $j = 1\ Kc\ j\ Qc$	9 and 34 bus feeder
Gholami *et al.*, 2015 [10]	Genetic algorithm (GA) with new coding and operators	Power factor correction, loss reduction, and voltage profile improvement	$Min\ [CEloss + CPloss + Ccapacitor]$	24-bus Network
Sayadi *et al.*, 2016 [11]	New P-PSO algorithm	Cost of power losses and reduction of harmonic distortion	$Min[Kploss + \sum KciQci]$	IEEE 33-bus and 77-bus distribution network
Shaheen and El-Sehiemy, 2017 [12]	Crow search algorithm	Reducing the energy loss, minimizing the loading level for the transformer substation, and cost	$MinF = Min(El \sum_{i=1}^{Nl} DlLoss\ + C_c \sum_{i=1}^{Nl} Qc)$	MV distribution networks
Youssef *et al.*, 2018 [13]	Salp Swarm Algorithm (SSA)	Cost of power losses Improving the voltage profile	$F1 = min(Ptloss)$ $F2 = min(Cost)$	Single line diagram of 69-bus and 85-bus radial distribution system.
Ivanov *et al.*, 2019 [14]	A comparison is made between five metaheuristic algorithms	Active power loss reduction The bus voltages	$F = min[f1(ploss) + f2(cost)]$	IEEE 33-bus system and on a real 215-bus EDN from Romania
Sampangi and Thangavelu, 2020 [15]	Water cycle algorithm and Grey wolf optimizer	Reduction of network power loss, voltage deviation, and enhancement of voltage stability	$Min(f) = min\ Ploss$	practical Indian 28-bus, 47-bus, and 52-bus and standard 33-bus, 69-bus, and 85-bus radial distribution networks
Bilal *et al.*, 2021 [16]	The particle swarm optimization	Reducing the active and reactive power losses and the cost	$Fmin\ =\ CpPtotloss + CqQtotloss +\ CCtotloss$	IEEE standard networks (34 and 85 nodes)
Babanezhad *et al.* 2022 [17]	Mathematical Remora Optimization Algorithm (ROA)	Minimizing the cost of losses	$MinCost = Closs(/year) + Ccap, install(/year) + Copearation(/year)$	Networks of 33 bus and 69 bus
Azeredo *et al.*, 2023 [18]	Bee screening algorithm.	Minimizing power losses Improving the voltage profile	$Minf = MinPloss + MinmeanTHD + Minfault$	The IEEE 39 and IEEE 57 Bus

The use of advanced capacitor allocation techniques, such as dynamic allocation based on system needs, can help minimize energy losses and improve overall efficiency [19]. Comprehensive simulations and analyses are often necessary to determine the optimal capacitor configuration, taking into account load fluctuations, frequency variations, and other system-specific parameters. Capacitor allocation plays a crucial role in the design and optimization of electrical and electronic systems, contributing to ensuring reliable and efficient performance.

2.3. DG allocation

This subsection presents research publications focusing on minimizing losses in distribution networks through the allocation of distributed generation (DG), dependent on the availability of distributed resources, particularly for renewable sources [4]. Given the varied definitions of DG in existing literature, it becomes essential to discuss several aspects for a more precise definition. These include the purpose, technology, location, DG rating, power delivery area, environmental impact, operation mode, ownership, and DG penetration [20].

DG can be specifically defined as "electric power generated from demand and supply-side resources, significantly less than centralized generation, deployable throughout the distribution network to meet the energy demand of customers supplied by the system." Generally, distributed resources are connected near the load points or the utility side of the system to minimize the distance of the distribution network [21].

Each segment of the distribution network is represented as a combination of a resistance in series with a pure inductance. The radial configuration consisting of two buses forms the distribution network is presented in Figure 1. The impedance of any given segment "i" within this network is expressed in Figure 1.

The load flow in this type of network is done using a BIBC matrix (bus injection to branch current) to calculate the currents flowing through all branches of the network. For a busbar to which a load is connected, the apparent power S is represented by (1).

$$S_i = P_i + jQ_i \tag{1}$$

Where $i = 1,2,3, \dots, n$. The equivalent current charge corresponding to the kth iteration is represented by (2).

$$I_i^k = I_i^r + jI_i^l = \left(\frac{P_i + jQ_i}{V_i^k}\right)^* \tag{2}$$

Where V_i^k and I_i^k are the voltage load and current of the busbar for the kth iteration; I_i^l and I_i^r are the imaginary and real parts of the busbar load; (*) is the imaginary part of the busbar.

The currents at the busbar are determined through the equation, while the currents flowing through the branches are established by applying Kirchhoff's law to the examined distribution network [22]. To illustrate the method for calculating the BIBC matrix, a straightforward distribution network is employed as an example, consisting of 7 busbars and 6 branches, as depicted in Figure 2.

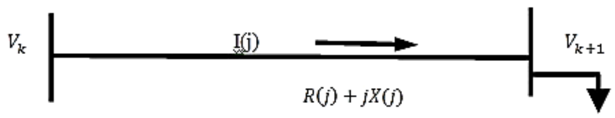

Figure 1. A radial configuration consisting of two buses forms the distribution network

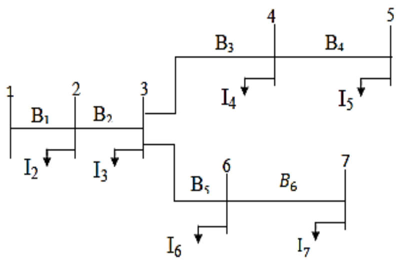

Figure 2. A simple distribution network of 7 busbars and 6 branches

2.4. DSTATCOM allocation

This subsection presents research publications related to minimizing losses in distribution networks through the allocation of distribution static compensator (DSTATCOM). As capacitor allocation does not significantly reduce losses, mainly due to the in-phase component of current and its focus on reactive current, DSTATCOM becomes essential for loss reduction and improving power quality [23]. DSTATCOM, functioning as a shunt customer power device in distribution networks, efficiently injects and absorbs reactive power [24].

Generally, DSTATCOM injects current at the point of common coupling in the network, addressing distribution issues by substantially reducing power loss, enhancing voltage profile (VP), correcting power factor, and reducing harmonics in distribution systems [25]. Given that the optimal allocation of DSTATCOM poses a complex combinatorial constrained optimization problem, various methods have been proposed by researchers to address this optimization challenge, as summarized in Table 2.

Table 2. Evolution in DSTATCOM allocation techniques

Author, year [ref]	Optimization approaches	Objective(s) type	Basic principle/objective function	Network
Hussain and Subbaramiah, 2013 [26]	An analytical approach for optimal location of DSTATCOM	Maintain the voltage magnitude as 1 p.u. supply the required reactive power for compensation	$minF=\frac{P_{loss}}{P'_{loss}} * 0.01 + \sum_{j=1}^{NB}[(Vi-Vmin)^2 + (Vi-Vmax^2]$	Single line diagram of a 33 bus radial distribution system
Taher and Afsari, 2014 [27]	Effective biologically inspired algorithm (Immune Algorithm)	Power loss reduction, and improvement of current and voltage profile in distribution networks	$Min\ f = RI2$	Single line diagram of IEEE 33-bus and 69 bus distribution system
Yuvaraj *et al.*, 2015 [28]	Harmony search algorithm to find the optimal location and sizing of Distribution STATic COMpensator	Minimizing the total network power losses	$Minimize(F) = min\ Ptloss$	Single line diagram of IEEE 33-bus
Gupta and Kumar, 2016 [29]	Revised network configuration aims to minimize power loss, thereby conserving energy and benefiting the environment	Energy Saving with improvement in voltage profile, reduction in power losses	$Minimize(F) = min\ Ptloss + minCost$	Single line diagram of IEEE 69 bus RDS
Yuvaraj *et al.*, 2017 [30]	Voltage stability index is used to search the optimal placement for installation of DSTATCOM y using bat algorithm.	Minimize the power loss. select the DSTATCOM size according to the load changes.	$Minimize(F) = min\ Ptloss$	Single line diagram of IEEE 69-and 33 bus system.
Yuvaraj and Ravi, 2018 [31]	The optimal size of DG and DSTATCOM are found by using a newly developed nature-inspired CSA in the RDS. The backward/forward sweep (BFS) algorithm is used.	Minimize the system total power losses and enhancing the bus voltages.	$Minimize(F) = min(\beta 1)$	One line diagram of IEEE 136-bus system
Selvaraj and Rajangam, 2019 [32]	The grey wolf optimizer (GWO) algorithm as a meta-heuristic technique is applied to solve the reconfiguration problem	Minimizing the total power loss and the load-balancing (LB) index of the radial distribution system	$F(x) = Min(\frac{P_{T.loss}^{R} + P_{T,Loss}^{D-statcom}}{P_{TLoss}}) + Min\frac{1}{nb}\sum_{j=1}^{n}(LB_{index})$	Single line diagram of IEEE 69-and 33 bus system.
Yuvaraj *et al.*, 2020 [33]	New methodology based on nature-enthused meta-heuristic optimization algorithm named as whale optimization algorithm (WOA)	Minimize the system's total power losses and total operating cost of DG and DSTATCOM	$Minimize(F) = min\ (\beta 1\Delta P_{TL}^{DG} + \beta 2\Delta OC)$	IEEE 33-bus and large 136-bus RDS
Zellagui *et al.*, 2021 [34]	Hybrid optimization methods that combine the firefly algorithm (FA) with various acceleration coefficients PSO	The considered objectives that reflect the technical, economic, and environmental issues, are active power loss level (APLL), short circuit level (SCL), voltage deviation level (VDL), net saving level (NSL), and environmental pollution reduction level (EPRL).	$MOF = Max\sum_{i=1}^{Nbus}\sum_{j=2}^{Nbus}(A1.APL\ L_{ij} + A2V\mathrm{D}L_j + A3SCL_{ij} + A4NSL_{ij} + A5EPRL_G)$	Single line diagram of practical EDS in Adrar City 205-bus. A, IEEE 33-bus. B, IEEE 69-bus, C, Algerian 205-bus
Khan *et al.*, 2022 [35]	Improved bacterial search algorithm for distribution network optimization	Minimize power losses and improve voltage stability and profile	$F = Min\sum_{i=1}^{N}P_{loss}$	Single line diagram of IEEE 33 bus system.
Salimon *et al.*, 2023 [36]	Black widow optimization algorithm the black widow optimization algorithm	Minimize power loss while simultaneously evaluating various techno-economic parameters such as the voltage profile index (VPI), voltage stability index (VSI), and annual cost savings	$F = \sum_{i}^{nb}\|I_i\|^2 . r_i$	The IEEE 33-bus and 69-bus RDNs

It is observed from the literature that most of the researchers have concentrated on individual techniques previously considering power loss or energy loss minimization as a basic objective function. In recent years, the trend has been created by several researchers to obtain maximum potential benefits through simultaneous application of capacitor, DG, and DSTATCOM allocation techniques in the distribution networks [29], [31]. However, capacitor and DSTATCOM both will provide reactive power support to the distribution system; hence, simultaneous allocation of capacitor and DSTATCOM is not considered by the researchers and DNO. Also, it is not an economically viable solution to allocate capacitors. Since capacitor allocation does not reduce losses appreciably due to the in-phase component of current, and it deals only with the reactive current component [37]. However, the trend has been created by several researchers to allocate DSTATCOM in distribution [37]-[40] network for solving power quality problems, a cuckoo search algorithm is used in [41] for capacitor allocations in radial distribution networks.

3. RESULTS AND DISCUSSION

This article presents an exhaustive examination of existing methodologies encompassing reconfiguration, capacitor allocation, and DG allocation. Figure 3 presents the loss minimization methodologies adopted for optimal planning and operation of distribution systems. The methodologies for addressing these methods have been divided into four categories: i) classical optimization techniques, ii) analytical methods, iii) meta-heuristic techniques, and iv) hybrid optimization techniques.

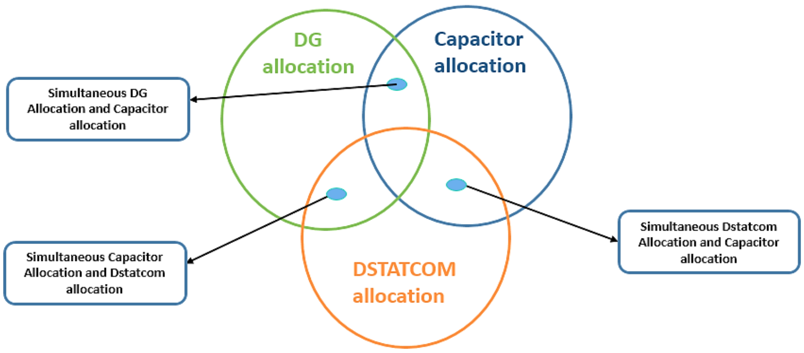

Figure 3. Methods for achieving minimal loss for optimal planning and operation of the distribution system

4. CONCLUSION

This article presents a complete survey of state-of-the-art methodologies for the solution of distribution network reconfiguration, capacitor allocation, distributed generators (DG) allocation, and distribution static synchronous compensators (DSTATCOM) allocation for loss minimization in distribution networks. The status and relevant background are identified and reviewed in detail together with the practical demands. The article draws on research articles spanning the last four decades and synthesizes the progressive developments in this field. The citations presented herein represent a sampling of the current technical assessments related to enhancing distribution system performance by achieving loss minimization and voltage profile enhancement. Since power systems are in a constant state of evolution, surveys on this topic need periodic updating. The above survey identified various techniques used to solve the problem as single, multi-objective approaches with different constraints. Following are the inferences drawn from the various techniques discussed in literature for distribution system loss minimization: i) Capacitor allocation is more suitable for a high voltage distribution network. This gives a simple reliable technique but having limited advantages due to the purpose of loss minimization only; ii) DG allocation focuses on integrating existing small-scale generations, which proves to be highly efficient, particularly for the integration of isolated small photovoltaic plants or wind farms into the distribution system. However, its implementation requires effective techniques, and its reliability during installation is comparatively lower; and iii) Because of the various advantages over the conventional capacitor allocation, DSTATCOM allocation in the distribution networks has drawn much attention. However, it needs some effective techniques for its implementation, installation, and control strategy. Considering the above-mentioned benefits, simultaneous approaches are the best strategy among those methods proposed in the literature in order to improve system performance. In addition, the installations of both DG and DSTATCOM together in distribution networks have been attracting attention in distribution networks to achieve higher system benefits. In the upcoming years, the simultaneous reconfiguration with DG and DSTATCOM allocation in the distribution network will draw more attention from distribution network operators as well as from researchers interested in the field.

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C : **C**onceptualization	I : **I**nvestigation	Vi : **Vi**sualization
M : **M**ethodology	R : **R**esources	Su : **Su**pervision
So : **So**ftware	D : **D**ata Curation	P : **P**roject administration
Va : **Va**lidation	O : Writing - **O**riginal Draft	Fu : **Fu**nding acquisition
Fo : **Fo**rmal analysis	E : Writing - Review & **E**diting	

CONFLICT OF INTEREST STATEMENT

The authors declare that there is no conflict of interest regarding the publication of this paper.

DATA AVAILABILITY

This study is a review article that synthesizes information from previously published research. All data used in this manuscript are available in the cited references.

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