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REVIEW ARTICLE

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Loss minimization techniques for optimal operation and planning of distribution systems: A review of different methodologies

Kola Sampangi Sambaiah | **Thangavelu Jayabarathi**

School of Electrical Engineering, Vellore Institute of Technology, Vellore, Tamilnadu, India, 635014

Correspondence
Thangavelu Jayabarathi, School of Electrical Engineering, Vellore Institute of Technology, Vellore, Tamilnadu, India-635014.
Email: tjayabarathi@vit.ac.in

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Summary
In an electrical power system, the generated power is transferred through a high voltage transmission system, and it reaches the low voltage consumers at the distribution side. In a distribution system, I^2R loss is very high compared with the transmission system due to high $^R/_X$ ratio, high current, and low voltage. It is a known fact that the economic enticement of distribution companies (DISCOMs) is to minimize losses in their networks. In general, this enticement is the difference in cost obtained between real and standard losses. Thus, when real losses are more than the standard losses, the DISCOMs are penalized economically, or when the opposite occurs, they earn a profit. Hence, loss minimization problem in distribution systems is a well-suitable researched topic for researchers. Various approaches are investigated and implemented to solve the loss minimization problem in the past. However, these are different from each other by choice of loss minimization tool, problem formulation, methods employed, and the solution obtained. Several methods exist for loss minimization like capacitor allocation, network reconfiguration, distributed generation (DG) allocation, feeder grading, high voltage distribution system, etc. The present article gives a literature review, general background, and comparative exposition of the most often used techniques: (a) network reconfiguration, (b) capacitor allocation, (c) DG allocation, and (d) DSTATCOM allocation for loss minimization in distribution system and its combination versions for achieving maximum potential benefits are (e) simultaneous reconfiguration and capacitor allocation, (f) simultaneous reconfiguration and DG allocation, (g) simultaneous DG and DSTATCOM allocation, and (h) simultaneous reconfiguration, capacitor, and DG allocation based on several published articles. This will make the literature easy to new researchers working in this area.

KEYWORDS
capacitor allocation, distributed generation allocation, distribution system, DSTATCOM allocation, loss minimization, network reconfiguration

1 | INTRODUCTION

Transmission and distribution (T&D) network losses are considered as the major consumption in any power system. Due to the exponential increase in the electricity demand, competitive energy market, and environmental constraints, the T&D systems are frequently being functioned under overloaded conditions, and losses in the distribution system have become a major concern. To achieve economic benefits entirely, the essential conditions to provide acceptable power quality and improved efficiency have created a very promising environment for the requirement of loss minimization techniques and state-of-the-art operational practices. The total power received by the distribution system is the difference between the total power generation and the transmission power losses. Power loss minimization is the only alternative to improve the efficiency of the distribution system. Thus, it is observed that from the past few decades several researchers have focused on distribution system loss minimization and voltage stability. There are various techniques available in the literature for distribution system loss minimization. However, the most often used techniques such as (a) capacitor allocation (feasible in high voltage distribution systems), (b) network reconfiguration (feasible in low voltage distribution systems), (c) DG allocation (more attentive on integrating existing small generations for instance, when an isolated small photovoltaic plants or wind farms penetrate the distribution system), (d) DSTATCOM allocation and its combination versions for achieving maximum potential benefits are (e) simultaneous reconfiguration and capacitor allocation, (f) simultaneous reconfiguration and DG allocation, (g) simultaneous DG and DSTATCOM allocation, and (h) simultaneous reconfiguration, capacitor, and DG allocation are discussed here. Traditionally, loss minimization has mainly concentrated on network reconfiguration optimizing or capacitor allocation for reactive power support. However, due to the penetration of DG, passive distribution networks are changed to active. Although DG allocation limits the distribution network operators (DNO) and inventors due to planning issues, the administrative system, and resources availability, governments are encouraging low carbon emission as a means of environmental protection and growing energy security. Since DGs have smaller unit size, occupy less area for installation, and can be fueled by renewable and nonrenewable source, they are steadily getting to be essential parts of the distribution system.[1]

In this review article, selected literature is gathered from IEEE transactions, Proceedings of IEE, proceeding conferences, and predominant technical journals such as International Journal of Electric Power System Research, Electrical Power and Energy Systems, Energy, etc. included. And also, exceptions were induced to append or include publication from other resources with unique significance and technical viewpoint on the relevant issue.

The rest of the review article is constituted as follows: Section 2 presents the methodologies for network reconfiguration, capacitor, DG, and DSTATCOM allocation techniques for planning and operation in distribution networks. Section 3 presents the methodologies for simultaneous network reconfiguration, capacitor, DG, and DSTATCOM allocation techniques for planning and operation, Section 4 discusses the impact of aforementioned methodologies on power loss and voltage profile, and various techniques for solving reconfiguration, capacitor, DG, and DSTATCOM allocation. Section 5 concludes the article with future works for solving distribution network optimization problem in light of present methodologies.

2 | METHODOLOGIES FOR NETWORK RECONFIGURATION, CAPACITOR, DG, AND DSTATCOM ALLOCATION TECHNIQUES FOR PLANNING AND OPERATION

Several methods have been implemented for the operation and planning of distribution networks. In this section, various methodologies for network reconfiguration, capacitor, DG, and DSTATCOM allocation techniques for planning and operation in distribution systems are presented.

2.1 | Network reconfiguration

The research publications which are related to loss minimization by using network reconfiguration in low voltage distribution systems are presented in this subsection. It is a vital technique to minimize loss. In a primary distribution system, two switches are present: they are sectionalizing switches (closed switches) and tie switches (open switches). The process involved in network reconfiguration is the simultaneous operation of sectionalizing and tie switches in feeders which varies the topological structure. The main advantages of reconfiguration are:

1. service restoration during feeder faults
2. network maintenance through outages planning
3. network overload relief, bus voltage improvement, and
4. loss minimization.

The basic control action involved in reconfiguration is the switching operation. However, due to several candidate-switching combinations and discrete switch nature, reconfiguration is a complex problem. In general, classical methods prevent to solve this complex problem of reconfiguration due to radiality and discrete switch nature. Hence, the majority of the methods in the literature for solving this problem are based on heuristic techniques. In general, one can handle the process of reconfiguration through algorithm categorization in two types:

1. Branch exchange—The algorithm has to open and close candidate switch pairs and operates the system in a feasible radial configuration.
2. Loop cutting—The algorithm has to open candidate switches to attain a feasible radial configuration for the completely meshed system.

Several algorithms have been implemented based on branch exchange method for loss minimization in the literature. The concept of reconfiguration for loss minimization was first proposed in 1975 by Merlin and Back[2] through branch-and-bound. Shirmohammadi and Hong[3] in 1989 modified the above method for the same application. Civanlar et al[4] used a load flow method to evaluate the change in network loss during reconfiguration. Baran and Wu[5] considered network reconfiguration for two purposes: one is power loss minimization and other is load balancing. Hereafter, several researchers have proposed various methods for solving the network reconfiguration problem on different networks which are summarized in **Table** 1. Consequently, after going through the extensive literature survey, it can be noticed that for solving network reconfiguration problem, several researchers investigated and implemented various algorithms like genetic algorithm,[7] simulated annealing,[12] mixed-integer hybrid differential evolution,[13] ant colony search algorithm,[14] quadratic programming,[15] plant growth simulation algorithm,[16] particle swarm optimization,[17] harmony search algorithm,[18] bacterial foraging optimization algorithm,[19] firework algorithm,[20] cuckoo search algorithm,[21] and bat algorithm.[22] The method of network reconfiguration was considered as a complex decision-making process for DNO to choose; it often needs widespread numerical computation, and it also disturbs the protective device coordination. In the aforementioned network reconfiguration techniques, it is normally assumed that the coordination between the protective devices has not been disturbed after the reconfiguration, but actually, the planning and coordination of protective devices are only suitable for fixed configuration.[23]

2.2 | Capacitor allocation

The research publications which are related to loss minimization in distribution networks by using capacitor allocation are presented in this subsection. The method of capacitor allocation is found to be viable in high voltage distribution systems. The main advantages of capacitor allocation in electric distribution systems are:

1. power flow control,
2. power and energy loss minimization,
3. voltage stability improvement,
4. handles voltage profile, and
5. power factor correction.

The capacitor is a reactive power source which reduces the amount of inductive reactance of the line loading; it can minimize the reactive power losses by the allocation of shunt capacitors. Several researchers have carried out their research on capacitor allocation initially for voltage control and later for loss minimization.[24]

The major challenges in capacitor allocation techniques are:

1. appropriate selection of capacitor units,
2. location or placement of capacitors, and

TABLE 1 Evolution in network reconfiguration techniques

Author, Year [Ref]	Optimization Algorithm(s)	Initial Reconfiguration Approach	Objective(s) Type	Basic Principle/Objective Function	Merits	Demerits	Network
Merlin and Back, 1975,[2]	Exhaustive search method	The initial network is a meshed network with all closed switches. The closed switches are opened one at a time to attain new radial structure.	Power loss minimization	Branch and bound technique	Final configuration of the network is independent of initial switches state. Solution procedure gives a near optimum or optimum solution.	The method deals with approximations. Line equipment losses are not considered. Assumed negligible network voltage angles.	Typical urban radial distribution systems
Shirmohammadi and Hong, 1988,[3]	Heuristic method	The initial network is converted to the meshed network by closing all the switches. The optimal flow pattern is achieved by opening switches one after another.	Resistive line losses minimization	$\min \sum R\|J\|^2$	Prevents approximations. The solution converges to near optimum or the optimum solution. Final configuration of the network is independent of initial switches state.	Results of actual operating conditions may vary since the calculations were made in a different environment.	Realistic distribution systems
Civanlar et al, 1988,[4]	Load flow method	Switch exchange and evaluating the change in the loss.	Loss minimization	$P = R_{loop}\|\sum I_i\|^2 + Re\{2(\sum I_i) * (E_m - E_n)^*\}$	Simple formula with simplified assumptions for change in loss reduction. Eliminates the switching options which cause high loss or no change in loss reduction.	Successive application of this method will cause the simultaneous multiple switching operations; hence the implementation of this scheme is beyond the scope of this method.	Realistic three and two feeder systems
Baran and Wu, 1989,[5]	Heuristic method	Initially creates incumbent spanning tree (parent) and checks all possible trees (children) by branch exchange method.	Loss minimization and load balancing	Dist-Flow branch equations, forward and backward update schemes	A lossy system is selected to conduct loss reduction. Power flow and estimation methods for loss minimization can also be used for load balancing	Algorithm efficiency is depending on initial branch selection. The solution obtained by this method is locally optimal since the present scheme does not examine all the possible trees.	32-bus distribution system

(Continues)

TABLE 1 (Continued)

Author, Year [Ref]	Optimization Algorithm(s)	Initial Reconfiguration Approach	Objective(s) Type	Basic Principle/Objective Function	Merits	Demerits	Network
					since both are similar problems.		
Wagner et al, 1991,[6]	Linear programming (Transportation algorithm)	Variable load profile data with a constant power factor serve as input for the algorithm.	Loss minimization	Uniformly distributed load model with seasonal variation	Ease to implement for large systems. Applicable for both lumped and uniformly distributed loads.	This method is applicable for only linear objectives and linearly independent associated costs. Compared with other methods, it is a more time consuming one.	A small three feeder and a large Kingston Public Utility Commission 44-kV distribution systems
K Nara et al, 1992,[7]	Genetic algorithm (GA)	In the open loop distribution system, the radial feeder is divided into load sections using sectionalizing switches and connects other feeders via tie switches.	Loss minimization	Distribution loss minimum and reconfiguration	Nature inspired algorithm. Less parameter tuning and feasible for a large system.	The solution obtained is near optimal. Slow convergence. The solution depends on the parameter values.	Realistic distribution system
Sarfi et al, 1993,[8]	Eigenvector approach and sanchis interchange method	Before performing optimization, the system is partitioned into system blocks.	Loss minimization	System partition technique has been implemented.	Overcomes the limitations on size imposed by the previous methods.	The solution obtained by the algorithm is near optimal because it does not work so well for varying loads.	35-bus distribution system
Taleski et al, 1997,[9]	Heuristic method	The initial network is converted to the loop by closing open tie switch and opening the sectionalizing switch for minimum energy loss.	Power and energy loss minimization	Branch exchange techniques	Serves as an auxiliary method for planning and operation purposes instead of loss minimization methods.	Due to the combinatorial nature of the problem needs complicated mathematical techniques. Requires more computational time.	16-bus and 32-bus distribution systems
McDermott et al, 1999,[10]	Heuristic nonlinear constructive method	Initially open all operable switches, and at every step, switches are closed for attaining the minimum value of	Loss minimization	The objective function is to minimize the ratio of loss increment and serving load increment.	An attempt has been made to operate switches in nontraditional schemes. Avoids sequential switching. The	In finite run time, there is no guarantee of obtaining a global optimum solution. Not feasible for large systems.	32-bus distribution system

(Continues)

TABLE 1 (Continued)

Author, Year [Ref]	Optimization Algorithm(s)	Initial Reconfiguration Approach	Objective(s) Type	Basic Principle/Objective Function	Merits	Demerits	Network
		the objective function.			network is built into a stage using a depth-first or best-first algorithm.		
Kashem et al, 2000,[11]	Heuristic method	Determines the permissible combination of switches for the possible combinations, individual switch status attainment, and identification of the optimal or near-optimal solution.	Voltage stability enhancement	The objective function is to enhance voltage stability	Eliminates the installation cost of additional equipment. Requires less computation time and memory.	No guarantee of an optimal solution.	69-bus distribution system
Young-Jae Jeon et al, 2002,[12]	Simulated annealing (SA)	In this method, the cost function is augmented with the distribution system operating conditions, perturbation mechanism is improved with system topology, and the polynomial-time cooling schedule is used which is based on statistical calculation within the search solution.	Loss minimization	$Total\ loss = \sum \left(\frac{P_b^2 + Q_b^2}{V_b^2}\right) R_b$	Needs less computation time. Compatible for large and complex optimization problems.	It frequently needs an extend cooling schedule and a special approach to attain a solution.	32-bus distribution system and 148-bus Korean electric power corporation (KEPC) distribution system.
Ching-Tzong Su et al, 2003,[13]	Mixed-integer hybrid differential evolution (MIHDE)	A simple method based on a random search, where the function parameters are programmed as a floating-point variable.	Loss minimization	$\min f = min(P_{T,Loss})$	The proposed method achieves minimum power loss with prescribed voltage limits. It determines network topology that minimizes the loss according to load pattern.	Attains optimal solution by consuming more computation time.	Taiwan Power Company (TPC) distribution network

(Continues)

TABLE 1 (Continued)

Author, Year [Ref]	Optimization Algorithm(s)	Initial Reconfiguration Approach	Objective(s) Type	Basic Principle/Objective Function	Merits	Demerits	Network
Ching-Tzong Su et al, 2005,[14]	Ant colony search algorithm (ACSA)	The method is based on ant colonies searching, finding, and carrying food to their nests.	Loss minimization	$\min f = min(P_{T,Loss})$	Enhanced optimization technique. Compatible for large and complex optimization problems.	Selection and parameter tuning are complex.	TPC distribution network
Taylor et al, 2007,[15]	Quadratic and quadratic constrained programming	The method is based on convex optimization algorithms.	Loss minimization	$\min_{p,q,y,z} \sum_{(i,j)} r_{ij}\left(p_{ij}^2 + q_{ij}^2\right)$	Quadratic programming gives an efficient and reliable solution for large systems.	Methods are computationally expensive.	32-bus and 70-bus test systems
Chun Wang et al, 2008,[16]	Plant growth simulation algorithm (PGSA)	The switches are defined in four different states so as to minimize the chance of unfeasible solution in the iteration process to improve efficiency.	Loss minimization	$\min f = min(P_{T,Loss})$	Reduces the computational time and eliminates the unfeasible solution based on the different switch state. Also avoids external parameter tuning.	Algorithm suffers from premature convergence.	33-bus and TPC 83-bus distribution systems.
Abdelaziz et al, 2009,[17]	Particle swarm optimization (PSO)	The method is based on swarming behavior with simple mathematical equations.	Loss minimization	$\min Z = \sum r_b\left(\frac{P_b^2 + Q_b^2}{V_b^2}\right)$	Requires less computation time. It restricts the topology to be radial for each trial solution. Also, the penalty function is not required in case of constraints violation. Derivative-free, flexible to integrate with other optimization techniques, and less sensitive to	Selection and parameter tuning are complex.	16-node, 32-node, and 69-bus distribution systems

(Continues)

TABLE 1 (Continued)

Author, Year [Ref]	Optimization Algorithm(s)	Initial Reconfiguration Approach	Objective(s) Type	Basic Principle/Objective Function	Merits	Demerits	Network
					the nature of the objective function.		
Rao et al, 2011,[18]	Harmony search algorithm (HSA)	The algorithm is developed based on the conceptual musical process of obtaining a perfect state of harmony.	Loss minimization	$\min f = min(P_{T,Loss})$	Derivative-free optimization process. Applicable for large systems.	An extensive search has to be carried out for obtaining the global optimal solution.	33-bus and practical 119-bus distribution systems
Sathish Kumar et al, 2012,[19]	Bacterial foraging optimization algorithm (BFOA)	The method is based on BFOA used for feeder reconfiguration with loss minimization as objective.	Loss minimization	$P = R_{loop}\lvert\sum I_i\rvert^2 + Re\{2(\sum I_i) * (E_m - E_n)^*\}$	Well-suited for a combinatorial optimization problem. It can be used for fast restoration service in distribution automation schemes (DAS).	Involves more steps and complex mathematical equations.	33-bus distribution system
Mohamed Imran et al, 2014,[20]	Fireworks algorithm (FWA)	The method is based on FWA which is a searching algorithm used for identifying the best location of sparks.	Loss and voltage deviation minimization	$\min F = \min(P_{T,loss} + V_D)$	Faulty feeder analysis has been carried out. Involves simple mathematical equations.	Parameter tuning is needed. The solution obtained is near optimum or optimal solution.	33-bus and practical 119-bus distribution systems
Thuan Thanh Nguyen et al, 2015,[21]	Cuckoo search algorithm (CSA)	The algorithm is based on obligate brood parasitism of some species of a cuckoo which uses other host birds' nests for laying eggs.	Loss and voltage deviation minimization	$\min F = \min(P_{T,loss} + V_D)$	Requires less parameter tuning. Convergence probability also implemented.	The method is computationally expensive.	33-bus, 69-bus and practical 119-bus distribution systems.
Abdollah Kavousi-Fard et al, 2015,[22]	Bat algorithm (BA)	The algorithm is based on echolocation and food search behavior of bats.	Loss minimization and reliability indices evaluation	Multi-objective framework for loss minimization and reliability indices evaluation.	Requires less parameter tuning. Stochastic behavior of the loads has been modeled. Reliability of the system is maintained.	Requires more computational time.	32-bus and 69-bus distribution systems.

3. sizing of capacitors to achieve the following results, ie,

a. power loss minimization,
b. better voltage regulation, and
c. power factor control.

The method of varying the capacitive volt-amp reactive (VARs) with respect to the load variation has been recognized from the 1940s. Before the 50s, the capacitors are installed at the substation for loss minimization; however, the trend of installing capacitors near to the loads on the primary distribution feeders rather than at substation has been started from the decade of 50s. Evaluation of loss equation for capacitor allocation is explained by considering a uniformly loaded primary feeder. The single line diagram (SLD) of the uniformly loaded primary feeder is shown in **Figure 1**.

The elementary reactive loss equation is given by[25]

$$Total\ losses\ (due\ to\ reactive\ current) = min\int [I(1-x)]^2 R\, dx = \min\int i^2 R\, dx \tag{1}$$

where I is the reactive current at substation; x is the distance from the substation; R is the total resistance.

The above formula has been used in several literatures, in many forms for sizing and placement of capacitors so as to obtain reduced losses. Neagle and Samson[25] has proposed rule-of-thumb for capacitor allocation in 1956, and an extension to this Schmill[26] considered both switched and fixed capacitors allocation in a primary distribution feeder with uniformly distributed and randomly distributed loads for loss minimization without voltage regulation in 1965. Duran[27] has used the method which identifies when capacitors are not economically justified in 1968. In 1978, Bae[28] has used an analytical method for optimum reactive-compensation level and maximum reduction in yearly loss. The drawbacks of the aforementioned methods are:

1. limited reactive-load distribution,
2. usually feeder wire size is assumed to be uniform,
3. problem of voltage regulation is not considered,
4. restrictions in the number of capacitor consideration at a time,
5. solutions obtained considering these assumptions may vary what they get under real situations, and
6. practically not compatible (lack of generality).

In 1986, Grainger and Lee[29] have removed some unrealistic assumption made by previous researchers and implemented easily and readily modified, adapted, and extended based on system conditions, and also presented single radial feeder with possibly several sections for different wire sizes, and for any known reactive-load spread along the feeder irrespective of load distribution, one can determine the size and location of the shunt capacitors. In 1982, Bunch et al[30] developed a control strategy and digital processor algorithm for improved voltage control and reactive power compensation at both distribution substation and feeder level; also, this work has been advanced as a part of the development of the integrated distribution control and protection system prototype for electric power and research institute. In 1983, Grainger et al[31] introduced continually controlling, capacitive compensation strategy for a primary feeder which assists DAS being considered for implementation of electric utilities who heavily depend on substation-based computers for reactive power control primary distribution feeders. However, none of the aforementioned techniques have investigated for the capacity release benefits, effects of growth in load and load factor, during off-peak demand voltage rise issues, and change in energy cost. All these methodologies are not capable of identifying the optimal capacitors number, their type whether fixed or switched, and unavailability standard industry size of the capacitor. Hereafter, several researchers have proposed various analytical, heuristic, and evolutionary algorithms for solving the capacitor

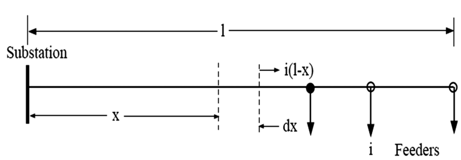

FIGURE 1 SLD of the uniformly loaded primary feeder

allocation problem on different distribution networks. The gradual evolution of capacitor allocation techniques is presented in **Table** 2.

It is observed from the aforementioned techniques for loss minimization through optimal location/placement and sizing of capacitors, one has to deal with conductor/feeder size, a number of capacitors, etc. and utility has to offer extra cost of the capacitor and for capacitor allocation techniques. Also, capacitor allocation does not reduce losses appreciably due to the in-phase component of current, and it deals only with the reactive current component.

2.3 | DG allocation

The research publications which are related to loss minimization in distribution networks by using DG allocation which depends on the availability of distributed resources (for renewable resources) are presented in this subsection. Several researchers gave various definition for DG in the literature; therefore, to define DG more precisely different issues have to be discussed, which are the purpose, the technology, the location, the DG rating, the power delivery area, the environmental impact, the operation mode, the ownership, and the DG penetration. DG can be defined as "The electric power generated from demand- and supply-side resources which are sufficiently lesser than the centralized generation that can be deployed throughout the distribution network to meet the energy demand of the customers supplied by the system." In general, distributed resources are connected near the load points or the utility side of the meter.[51,52]

In recent years, the integration of distributed generators (DGs) into distribution network has increased at a rapid pace. The rise in high penetration of DG is shifting the grid model away from the traditional centralized systems. The impacts of DG penetration into existing distribution network are classified based on three major aspects which are environmental, economic, and technical impacts. These impacts are presented in **Table** 3. It is also noticed that inappropriate allocation of DG adversely affects the network performance. Thus, to maximize DG allocation benefits, it is necessary to identify the appropriate size and location in distribution systems for DG allocation without disturbing the current system infrastructure. The IEEE 1547 standards for interconnection and interoperability of DG/distributed energy resources (DER) into existing electric power systems (EPSs) are presented in **Table** 4.[53] Hence, the problem of DG allocation has become a major challenge for DNO and researchers in the field. Several researchers have investigated and implemented various methodologies/techniques for solving this optimization problem are summarized in **Table** 5.

2.4 | DSTATCOM allocation

The research publications which are related to loss minimization in distribution networks by using Distribution static compensator (DSTATCOM) allocation are presented in this subsection. 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, DSTATCOM is used for loss reduction and power quality improvement. DSTATCOM is a shunt customer power device used in distribution networks which is capable of injecting and absorbing reactive power with fast and efficient manner. In general, DSTATCOM injects current at point of common coupling in the network which helps in overcoming distribution problem through a substantial reduction in power loss, VP enhancement, power factor correction, and harmonic reduction in distribution systems.[85] Since the optimal allocation of DSTATCOM is also a complex combinatorial constrained optimization problem, several researchers have proposed various methods for solving this optimization problem as summarized in **Table** 6.

The concept of DSTATCOM allocation in distribution systems is grasping more attention from research society as well as DNO in recent years. However, it requires effective techniques for implementation, installation, and control strategy of DSTATCOM.

So, it can be observed from the literature that loss minimization method is grasping more attention due to its vital benefit of network loss minimization along with the provision of supplying electrical energy to the network for demand crisis. The widespread study of all aforementioned loss minimization techniques impact on distribution network is summarized in **Table** 7.

This section discussed the individual techniques of network reconfiguration, capacitor, DG, and DSTATCOM allocation for power loss minimization. So, in the next section, simultaneous reconfiguration with capacitor, DG, and DSTATCOM have been presented.

TABLE 2 Gradual evolution in capacitor allocation techniques

Author, Year [Ref]	Optimization Approach/ Algorithm	Specific Feature/ Noteworthy Contributions	Objective(s) / Capacitor Type	Basic Principle/ Objective Function	Advantages/Merits	Demerits	Network
Neagle and Samson, 1956,[25]	Rule-of-thumb	Maximum loss reduction can be achieved by installing a single capacitor bank of capacity equal to two-thirds of the KVAr load on the feeder.	Loss minimization/ shunt capacitors	$Total\ losses = \int i^2R\,dx$	Initiated the trend of shifting capacitors from the substation to near load points.	Considered only savings of peak kilo-watt loss. Not applicable for larger systems. No guarantee of an optimal solution.	Uniformly distributed load feeder
Schmill, 1965,[26]	Load flow method	The sequential process includes different methods for capacitor number, location, size, and timing.	Loss minimization/ shunt capacitors	$Total\ losses = \int i^2R\,dx$	Real and reactive power losses cost saving.	Voltage control problem has ignored. Uniform wire size.	Uniformly and randomly distributed loads of spots on the feeder
Duran, 1968, [27]	Dynamic programming (DP)	The developed method determines when the operation of capacitors is not economically justified.	Loss minimization/ fixed shunt capacitor banks	$F = \sum [SL_b(I_{cb}) - C(i_{cb})]$	Considered and studied special cases when no capacitor cost, cost proportional to installed capacity plus a fixed cost per installed bank and cost proportional to installed capacity.	Voltage control problem has ignored.	Radial distribution feeder with discrete lumped loads
Bae, 1978,[28]	Analytical method	The developed method works in a sequence of steps for loss reduction with both switched and fixed capacitor installation during varying load conditions.	Loss minimization/ nonswitched capacitor banks	A modified version of the objective used by Neagle and Samson	Optimal capacitor locations, loss reduction under annual varying load conditions, and reactive power compensation under a wide range of annual reactive load conditions.	Ignored voltage regulation problem.	Uniformly distributed load feeder
Grainger and Lee, 1981,[29]	Optimization technique implemented in a computer.	The method continually controlling, capacitive compensation strategy for a primary feeder which assists DAS being considered for implementation of electric utilities who heavily depend on substation-based	Power and energy loss minimization/shunt capacitor banks	Equal area criterion	Optimal sizing and placement are independent of load distribution and applicable for any known reactive load, a number of units, and capacitor cost.	Not considered the capacity release benefits, effects of growth in load and load factor, during off-peak demand voltage rise issues and change in energy cost	Physically existing 23-kV nine-section feeder with five different wire sizes.

(Continues)

TABLE 2 (Continued)

Author, Year [Ref]	Optimization Approach/ Algorithm	Specific Feature/ Noteworthy Contributions	Objective(s) / Capacitor Type	Basic Principle/ Objective Function	Advantages/Merits	Demerits	Network
		computers for reactive power control primary distribution feeders.					
Bunch et al, 1982,[30]	DP	Controls voltage, reactive power, and feeder losses in an integrated mode according to specified priority.	Line loss minimization/ switched capacitors	$Line\ losses = \int i^2R\,dx$	Control and monitoring systems will offer the ability to respond to voltage and reactive power scheduling.	All controls are depending on priority.	Uniformly distributed load feeder
Grainger et al, 1983,[31]	DP	The method continuously controls, a capacitive compensation scheme for primary feeders which is implemented by electric utilities on substation-based computers.	Power and energy loss minimization/shunt capacitor banks	$S = K_pLP(I^0_{ci}, h_i) + K_eLE(I_{ci}(t), h_i) - K_c\sum I^0_{ci}$	Suitable for continuously varying capacitors on distribution feeders.	Complex mathematical equations.	Physically existing 23-kV nine- section feeder with five different wire sizes.
Sundhararajan et al, 1994,[32]	GA	The process based on natural evolution. The method starts iteratively maintaining a set of possible solutions to a specific problem.	Power and energy loss minimization/fixed and switched capacitors	$\min K_e \sum T_iP_i + K_pP_0 + K_c \sum C_j$	Computationally simple and robust search in complex problem spaces.	The solution of the algorithm is based on the stochastic generation of variables.	nine-bus and 30-bus distribution systems.
Huang et al, 1996,[33]	Tabu search (TS)	A sensitivity analysis method is used to determine candidate bus location to reduce search space. Bus voltage constraints are considered for different load levels.	Energy loss minimization/fixed and switched capacitors	To minimize capacitor investment cost and energy loss	Suitable for timely varying load levels on distribution feeders. Discussed the cost analysis of fixed and switched capacitors.	The solution obtained is near the optimal solution.	69-bus distribution system
Carlisle and El-Keib, 2000,[34]	Graph search algorithm	The method is based on possible moves in the graph for capacitor location and size.	Power and energy loss minimization/fixed and switched capacitors	$\max S = K_pLP + K_eLE - CC$	Discrete values of capacitor sizes are considered which are multiples of 150. Also identified the exact cost.	Considered constant real power flow.	Large radial distribution system.
Levitin et al, 2000,[35]	GA	The method starts iteratively maintaining a set of possible solutions to	Energy loss minimization/shunt capacitor	The objective function is depending on capacitor cost, capacitor number and power/energy loss.	Benefits due to the minimization of peak-load loss and	The solution of the algorithm is based on random generation of variables.	Radial distribution system.

(Continues)

TABLE 2 (Continued)

Author, Year [Ref]	Optimization Approach/ Algorithm	Specific Feature/ Noteworthy Contributions	Objective(s) / Capacitor Type	Basic Principle/ Objective Function	Advantages/Merits	Demerits	Network
		a specific problem. The mutation and crossover operators are used for better convergence and search space reduction.			energy loss are discussed.		
Das, 2002,[36]	GA	The optimal location and size of the capacitors are identified under varying load conditions on the distribution system.	Energy loss minimization/fixed and switched shunt capacitors	The objective function is a function of capacitor cost, load level, number of capacitors and power loss.	This method considered both fixed and marginal cost of the capacitor. Considered capacitor as both reactive power load and constant impedance load.	The solution of the algorithm is based on random generation of variables. Chances of premature convergence.	Radial distribution system.
Ching-Tzong Su and Chu Sheng-Lee, 2002,[37]	MIHDE	In this method, sensitivity factors are used to determine candidate bus location to reduce the number of alternatives to be examined.	Power loss minimization/shunt capacitors	$Cost = K_p P_{T,Loss} + \sum C_i^c$	The possible choices of capacitors size are presented well. The method is suitable for large systems.	The optimal solution is obtained by consuming more computation time.	Nine-bus distribution system
Mendes et al, 2005,[38]	Evolutionary-based memetic algorithm	The method is based on memetic behavior of evolutionary algorithms.	Power loss minimization/ capacitors	The fitness function consists of annual cost and deviation in the budget.	The capacitor allocation will change each and every time when a local search is performed.	The inverse process of capacitor allocation.	Nine-bus and 135-bus distribution systems.
Hamouda et al, 2010,[39]	Heuristic method	The method is operated for two stages: sensitivity analysis for candidate bus location (first stage) and optimal size based on maximum savings (second stage).	Loss minimization/ shunt capacitors	Multi-objective optimization (MOOP)	Overcompensation problem has solved.	The solution obtained by the heuristic method is near the optimal solution.	Nine-bus and 69-bus distribution systems.
R. S. Rao et al, 2011,[40]	PGSA	The solution methodology has two parts: one is the sensitivity analysis method for candidate bus location and other is an	Loss minimization/ shunt capacitors	$Cost = K_p P_{T,Loss} + \sum \left(C_i^c + K_{cf}\right)$	Free from external tuning parameters. It handles constraints and objective function separately.	Computational complexity not discussed.	10-bus, 34-bus, and 85-bus distribution systems.

(Continues)

TABLE 2 (Continued)

Author, Year [Ref]	Optimization Approach/ Algorithm	Specific Feature/ Noteworthy Contributions	Objective(s) / Capacitor Type	Basic Principle/ Objective Function	Advantages/Merits	Demerits	Network
		optimization algorithm for capacitor sizing.					
S. A. Taher et al, 2011,[41]	PSO	The method is developed to improve power quality.	Power and energy loss minimization/fixed shunt capacitors	The objective function is a function of power loss, capacitor cost, and capacity.	The method uses a wider search space. Total harmonic distortion (THD) is reduced.	The method is suffering from premature convergence problem.	18-bus and 33-bus distribution systems.
M. R. Raju et al, 2012,[42]	Direct search algorithm (DSA)	The sequential method depending on direct search is used for voltage improvement and to maximize net savings.	Power loss minimization/fixed and switched capacitors	$\min S = K_e \sum T_i P_i + \sum (K_c Q_{ci})$	The method is feasible for standard and practical distribution systems.	Capacitor installation and maintenance costs are excluded from net savings.	Standard 69-bus, 85-bus distribution systems, and a practical 22-bus distribution system.
Attia El-Fergany, 2013,[43]	Evolutionary algorithms (differential evolution and pattern search approach)	The method is used for optimal sizing of shunt capacitors where the location is predefined. Here, high potential candidate buses are pre-identified by sensitivity factor analysis methods.	Energy real power loss minimization/shunt capacitors	$\min\{C_e P_{L-a} T + C_{cI} N_B + C_c \sum Q(i)\}$	The method is accurate and reliable with reducing search space and computational time.	Harmonic and line stray capacitors effects neglected.	34-bus and 69-bus distribution systems.
S Sultana et al, 2014,[44]	Teaching and learning-based optimization (TLBO)	The method is a population-based algorithm in which two important phases are teaching and learning.	Power loss and energy cost minimization/ shunt capacitors	$\min S = K_e \sum T_i P_i + \sum (K_c Q_{ci})$	Guaranteed solution. Suitable for large systems.	The convergence rate is depending on the teaching factor.	Standard 69-bus, 85-bus, 141-bus distribution systems, and a practical 22-bus distribution system.
Chu-Shen Lee et al, 2015,[45]	PSO	The method employs PSO approaches with operators based on Cauchy and Gaussian probability distribution functions for capacitor placement with chaotic sequences for a given load pattern.	Energy loss minimization/shunt capacitors	$Cost = K_p P_{T,Loss} + \sum C_i^c$	Requires less computation time compared with exhaustive search algorithms. Widely used for solving various complex combinatorial optimizations.	Parameter tuning and premature convergence are two frequently facing problems.	Nine-bus and 33-bus distribution systems.
S. K. Injeti et al, 2015,[46]	BA and CSA	In this method, two bio-inspired algorithms have been used for optimal	Real power loss minimization/shunt capacitors	A modified version of the objective function used by Attia El-Fergany in[43]	The optimal capacitor sizes chosen are standard sizes that are available in the market.	Parameter tuning is complex since both require more parameters to be tuned.	34-bus and 85-bus distribution systems.

(Continues)

TABLE 2 (Continued)

Author, Year [Ref]	Optimization Approach/ Algorithm	Specific Feature/ Noteworthy Contributions	Objective(s) / Capacitor Type	Basic Principle/ Objective Function	Advantages/Merits	Demerits	Network
		location and sizing of shunt capacitors.					
K. R. Devabalaji et al, 2015,[47]	BFOA	A sensitivity analysis method is used to determine candidate bus location and BFOA is used for the optimal size of the capacitor on the distribution system with varying load levels.	Power loss minimization/shunt capacitors	$\min(P_{T,loss}) = min \sum P_{loss}(i,i+1)$	The curve fitting technique for adjusting capacitor size according to the load changes.	Thermal capacity of lines not considered. Tuning of parameters and premature convergence are two problems.	34-bus and 85-bus distribution systems.
N. Gnanasekaran et al, 2016,[48]	Shark smell optimization (SSO)	The method is based on the hunting behavior of sharks in an ocean by the smell of prey blood.	Energy loss minimization/shunt capacitors	$minimize\ F = cost\ of\ energy + cost\ of\ capacitors$	Applicable for practical systems. Ease of implementation with simpler formulations.	Considered inappropriate load levels for system conditions.	34-bus and 118-bus distribution systems.
D. B. Prakash et al, 2017,[49]	Whale optimization algorithm (WOA)	The method uses two operators: searching and encircling these operators mimics the whales' food search behavior in an ocean. This is used for solving the optimal capacitor allocation problem.	Line loss minimization/shunt capacitors	$Cost = K_p P_{T,Loss} + \sum K_C Q_{pC}$	External tuning of parameters is not required. Suitable for large systems.	Objective functions are not contradictory.	34-bus and 118-bus distribution systems.
V. Tamilselvan et al, 2018,[50]	Flower pollination algorithm (FPA)	The method is based on the pollination process of flowering plants. This method is suitable for both local and global search.	Total power loss minimization/shunt capacitors	$Cost = K_p P_{T,Loss} + \sum K_C Q_o^C$	Computationally efficient and code ready optimization algorithm for solving various complex optimization problems.	Fixed parameter setting for all the test cases.	33-bus, 34-bus, 69-bus, and 85-bus distribution systems.

TABLE 3 Impacts of DG integration into distribution network

Impact Type	Nonrenewable/Conventional DG	Renewable/Nonconventional DG
Environmental		
Reduction of greenhouse gases		✓
Economic		
Deferring in power system expansion	✓	✓
Electricity tariff reduction	✓	✓
Upgraded productivity	✓	✓
Healthcare investment reduction		✓
Reduced fuel expenses		✓
Auxiliary supply	✓	✓
Peak shaving	✓	✓
Enhanced production for critical loads	✓	✓
DG dispatch flexibility	✓	
Technical		
Loss minimization	✓	✓
Voltage stability	✓	✓
Reverse power flow	✓	✓
System security and reliability	✓	
Power quality	✓	✓

TABLE 4 IEEE 1547 standards for interconnection and interoperability of DG/DER[53]

Standard	Description	Year
IEEE Std 1547	Standard for interconnection of DER with EPSs	2003 and 2014
IEEE Std 1547 (Full version)	Draft Std for interconnection and interoperability of DER with associated EPS interfaces	2003
IEEE Std 1547.1	Conformance test procedure for equipment interconnection of DER with EPSs	2005
IEEE Std 1547.2	Application guide for IEEE 1547 standard	2008
IEEE Std 1547.3	Guide for control and monitoring information exchange of DER with EPSs	2007
IEEE Std 1547.4	Guide for design, operation, and interconnection of island mode DER with EPSs	2011
IEEE Std 1547.6	Recommended practice for interconnecting of DER with EPSs distribution secondary networks	2011
IEEE Std 1547.7	Guide to conducting distribution impact studies for DER interconnection	2013
IEEE Std 1547.8	Draft recommended practice for creating methods and procedures that offer supplementary support for implementation strategies for extended use of IEEE Std 1547-2003	2014

3 | METHODOLOGIES FOR SIMULTANEOUS NETWORK RECONFIGURATION, CAPACITOR, DG, AND DSTATCOM ALLOCATION TECHNIQUES FOR PLANNING AND OPERATION

Recent works on network reconfiguration involved detailed studies on the optimization of capacitor, DG and DSTATCOM sizes, and its locations for installation are presented in this section. Here, the simultaneous techniques for network power or energy loss minimization and voltage profile improvement are considered as the main objectives. These techniques attracting the researchers and DNO for achieving maximum techno-economic benefits.

TABLE 5 Gradual evolution in DG allocation techniques

Author, Year [Ref]	Optimization Approach/ Algorithm	Contributions	Objective(s) / DG Type	Basic Principle/ Objective Function	Advantages/Merits	Demerits	Network
Rau and Wan, 1994,[54]	Analytical approach	The second-order method is used to compute the resource capacity to achieve required optimizing objectives.	Minimization of losses, Var losses, or loadings in selected lines/ Renewable	$min\ F = min \sum P_{loss}$	The iterative process with stepwise increasing source capacity for losses minimization.	The iterative process is lengthy. No guarantee of convergence. Not suitable for large systems in terms of computation.	Six-bus 25-kV distribution network.
Willis, 2000,[55]	Analytical method and rules-of-thumb (2/3 rule or Golden rule)	The method suggested that a DG of capacity two-thirds of the system is installed at two-thirds distance of the feeder length.	Minimization of real and reactive losses/ Conventional	Zero-point analysis	Easy to apply.	The approach is not feasible in case of load varying conditions.	Radial distribution network
Jabr and Pal, 2009,[56]	Heuristic method based on ordinal optimization	The method has several forms which are loss minimization, DG capacity maximization, and combination of both.	Minimization of loss/ Conventional	$maxC_{DG} \sum P_{DG}+C_L(P_{L(target)} - P_{L(actual)})$	Cost analysis of DG installation and financial incentives for DNO are explained.	Complex mathematical equations are involved.	69-bus distribution system.
S. Ghosh et al, 2010,[57]	Conventional iterative search technique	The method is focused on the reduction of both DG cost and network loss.	Minimization of loss/ Conventional	$OF = C(P_{DG})+W \times E$	Substantial reduction of DG cost and losses is achieved.	The results are based on the weighting factors.	Six-bus, 14-bus, and 30-bus distribution systems.
D. Q. Hung et al, 2010,[58]	Analytical method	Single DG allocation	Minimization of loss/ Conventional	Exact loss formula	Quick in losses calculation. No problem with convergence.	The method is not robust.	16-bus, 33-bus, and 69-bus distribution systems.

(Continues)

TABLE 5 (Continued)

Author, Year [Ref]	Optimization Approach/ Algorithm	Contributions	Objective(s) / DG Type	Basic Principle/ Objective Function	Advantages/Merits	Demerits	Network
M. M. Aman et al, 2012,[59]	Analytical approach	The overall system capacity improved by loss reduction and voltage profile improvement.	Minimization of line losses/ Conventional	$min\{\sum\lvert I_b\rvert^2 R_b\}$	Computationally efficient method.	Convergence characteristics of the method are not mentioned.	12-bus, modified 12-bus, and 69-bus distribution systems.
D. Q. Hung et al, 2013,[60]	Analytical strategy method	The method used both dispatchable and nondispatchable renewable sources for integration.	Minimization of energy loss/ Renewable	Elgerd's loss formula	DG sources with lead, unity, and lag power factors are placed based on their availability.	Complex mathematical equations need to be solved for modeling of renewable sources.	69-bus distribution system.
Moravej and Akhlaghi, 2013,[61]	CSA	The algorithm is based on obligate brood parasitism of some species of a cuckoo which uses other host birds' nests for laying eggs.	Minimization of loss/ Conventional	Weighted aggregate multi-objective optimization	Less parameter tuning. Convergence is free from parameters.	Fixed DG sizes are chosen for allocation.	38-bus and 69-bus distribution systems.
S. H. Lee et al, 2013,[62]	Kalman filter algorithm	The method used power loss sensitivity, its derivatives, and power margin for location and Kalman filter for size.	Minimization of loss/ Conventional	Multiple DG allocation	Computationally efficient during optimization process since it requires only a few samples of data.	The solution obtained is near optimal solution since DG size is discrete.	31-bus and Korean Do-gok distribution networks.
Kansal et al, 2013[63]	PSO	The method is based on swarming behavior. It consists of simple mathematical equations.	Minimization of loss/ Conventional	Multiple DG allocation	Suitable for different type of DG sources installation in distribution network with variable power factor.	Parameter tuning and premature convergence are two frequently facing problems.	33-bus and 69-bus distribution systems.

(Continues)

TABLE 5 (Continued)

Author, Year [Ref]	Optimization Approach/ Algorithm	Contributions	Objective(s) / DG Type	Basic Principle/ Objective Function	Advantages/Merits	Demerits	Network
Viral and Khatod, 2015,[64]	Analytical approach	The analytical approach is based on the self-correction algorithm requires fewer iterations.	Minimization of loss/ Conventional	Multiple DG allocation	Requires less computational time.	This method is not applicable to unbalanced and meshed networks. The solution obtained is near optimal solution since search space is reduced.	15-bus and 33-bus distribution systems.
Mena and Garcia, 2015,[65]	Heuristic approach based on relaxed mixed integer nonlinear programming (MINLP)	The algorithm works on two stages: firstly, for search space reduction using the *fmincon* function of MATLAB® and secondly, minimization of objective function based on DG location.	Minimization of loss/ Conventional	Multiple DG allocation	Multiple DG allocation for loss and generation costs minimization.	Considered approximation model for reducing search space.	69-bus and 118-bus distribution systems.
Karatepe et al, 2015,[66]	Power flow analysis-based probabilistic assessment	The concept includes allocation of single and multiple DG with uncertainties for finding power loss, voltage profile, and line loss.	Minimization of line losses/ Conventional	Single and multiple DG allocation with uncertainties	Simple power flow method based on priorities. Threshold penetration level is identified.	Considered on system uncertainties but not DG output.	30-bus, 34-bus, and 57-bus distribution systems.
Abu-Mounti and El-hawary, 2011,[67]	Artificial bee colony (ABC) algorithm	The method is based on an artificial bee colony for DG allocation in distribution network with varying load conditions.	Minimization of total real power loss/ Conventional	$Obj.Fun = min\sum R_b \left(\frac{P_b^2+Q_b^2}{V_b^2}\right)$	Fewer parameters to be tuned.	Success rate is depending on effective parameter tuning.	69-bus distribution system.

(Continues)

TABLE 5 (Continued)

Author, Year [Ref]	Optimization Approach/ Algorithm	Contributions	Objective(s) / DG Type	Basic Principle/ Objective Function	Advantages/Merits	Demerits	Network
Sultana and Roy, 2015,[68]	Oppositional krill herd (OKH) algorithm	The method is a mix of krill herd and oppositional learning-based algorithms.	Minimization of annual energy loss/ Renewable	$E_{loss} = 365 \sum t \times P_{loss}$	The method has allocated biomass, solar, and wind-based DG units for loss reduction. It also avoids the premature convergence problem in krill herd algorithm.	Self-compared algorithm results.	33-bus, 69-bus, and 118-bus distribution systems.
Sudabattula and Kowsalya, 2016,[69]	BA	The algorithm is based on echolocation and loudness aspects used by bat for food search.	Minimization of power loss/ Renewable	$obj.\ fun = \min(P_{loss})$	Bat algorithm is used for optimal allocation of solar PV arrays in the distribution system.	Convergence characteristics not been discussed. Insufficient data for PV modeling.	33-bus distribution system.
Sultana et al, 2016,[70]	Grey wolf optimizer (GWO)	The algorithm uses searching, encircling and attacking operators for hunting the prey.	Minimization of reactive power losses/ Conventional	Multiple DG allocation	Better convergence with less parameter tuning. Suitable for solving other complex combinatorial optimization problems.	Consume more computational time.	69-bus distribution system.
Reddy et al, 2016,[71]	FPA	The method is based on the pollination process of flowering plants. This method is suitable for both local and global search.	Minimization of loss/ Conventional	$minf = \min\left(P^T_{loss}\right)$	Computationally efficient and code ready optimization algorithm for solving various complex optimization problems.	Convergence characteristics not been discussed. Fixed parameter setting for all the test cases.	15-bus, 34-bus, and 69-bus distribution systems.
Kowsalya et al, 2014,[72]	BFOA	A sensitivity analysis method is used to determine candidate bus location, and BFOA is used for the optimal size of the DG.	Minimization of network power loss/ Conventional	Multiple DG allocation	The method has achieved reduced power loss, operational cost, and improved voltage profile.	Parameters tuning and premature convergence are two problems.	33-bus and 69-bus distribution systems.

(Continues)

TABLE 5 (Continued)

Author, Year [Ref]	Optimization Approach/ Algorithm	Contributions	Objective(s) / DG Type	Basic Principle/ Objective Function	Advantages/Merits	Demerits	Network
Prabha et al, 2015,[73]	Intelligent water drop (IWD) algorithm	A loss sensitivity factor (LSF) analysis is used to determine candidate bus location, and IWD algorithm is used for the optimal size of the DG.	Minimization of total line losses/ Conventional	$minf = \min(\sum P_{loss})$	The algorithm has reduced total line losses.	Requires a greater number of parameters tuning.	10-bus, 33-bus, and 69-bus distribution systems.
Prabha et al, 2016,[74]	Invasive weed optimization (IWO) algorithm	LSF analysis is used to determine candidate bus location, and IWO algorithm is used for optimal DG size.	Minimization of real power losses/ Conventional	$min.\ f = min(\alpha_1 PL_{DG} + \alpha_2 V_D + \alpha_3 OC)$	The algorithm has minimized the power loss, voltage deviation, and overall operating cost.	Requires a greater number of parameters tuning.	33-bus and 69-bus distribution systems.
Tanvar et al, 2017,[75]	PSO	In this method, an analytical hierarchy process is used for appropriate weighing factors for different indices.	Minimization of real power losses/ Renewable	Weighted aggregated MOOP technique	The method has considered techno-economic and environmental benefits of renewable DG allocation in the distribution system.	Lack of comparison shows the results of the method are not valid.	51-bus distribution system.
Reddy et al, 2017,[76]	Antlion optimization (ALO) algorithm	The bio-inspired algorithm has been used for optimal DG sizing and placement.	Minimization of system power losses/ Conventional	$P_{loss} = \sum I_b^2 R_b$	The method achieved reduced system power losses and improved voltage profile.	Convergence characteristics not been discussed. Lack of results comparison.	15-bus, 33-bus, 69-bus, and 85-bus distribution systems.
Reddy et al, 2018,[77]	WOA	In this approach, the power loss index method is used to determine candidate bus location, and WOA algorithm is used for optimal DG size.	Minimization of power losses/ Conventional	$P_{loss} = \sum I_b^2 R_b$	The method achieved the reduced system power losses and improved voltage profile by allocating single DG.	Performance of optimization technique in terms of convergence characteristics not been discussed.	15-bus, 33-bus, 69-bus, 85-bus, and 118-bus distribution systems.

(Continues)

TABLE 5 (Continued)

Author, Year [Ref]	Optimization Approach/ Algorithm	Contributions	Objective(s) / DG Type	Basic Principle/ Objective Function	Advantages/Merits	Demerits	Network
Moradi and Abedini, 2013,[78]	A combination of GA and PSO with fuzzy	The method uses GA for location and PSO for the size of the DG. The fuzzy-based approach is used to convert multi-objective to single objection optimization.	Minimization of network power losses/ Conventional	Multiple DG allocation	The method achieved the loss reduction, better voltage regulation, and improved voltage profile within the system framework.	Self-compared results.	33-bus and 69-bus distribution systems.
Gandomkar et al, 2014,[79]	Genetic-based TS	The method uses GA for location and TS for the size of the DG.	Minimization of power losses/ Renewable	$min.\ f = \sum P_b$	The algorithm parameter setting does not impact on DG size and location.	Performance of optimization technique in terms of convergence characteristics not been discussed.	13-node and 34-node distribution test feeders.
Jamian et al, 2014,[80]	Evolutionary programming (EP) and PSO	The method is a combination of EP and PSO based on ranking mechanism.	Minimization of total power losses/ Renewable	Multiple DG allocation	The method avoids the weak solution set which reduces the number of iterations to be performed.	Suitable for lower dimensional mathematical benchmark functions only.	33-bus distribution system
Bikash Das et al, 2016,[81]	Symbiotic organisms search (SOS) algorithm	The method is based on a symbiotic relationship between different biological species.	Minimization of real power loss/ Renewable	$\mathrm{P_{loss}} = \sum \mathrm{real}\left(\mathrm{I_b^2 Z_b}\right)$	The algorithm is free from parameter tuning.	Computational time taken per iteration is high.	33-bus and 69-bus distribution systems.
Sanjay et al, 2017,[82]	Hybrid grey wolf optimizer (HGWO)	This method for GWO evolutionary operators has been used for hybridization and applied on distribution networks for optimal DG allocation.	Minimization of power loss/ Conventional	$P_{loss} = \sum R_b \left(\frac{P_b^2 + Q_b^2}{V_b^2}\right)$	DG units are classified based on the nature of power injection. Power loss reduction and voltage profile improvement are achieved through the allocation of different DG types.	The algorithm is not tested on standard mathematical benchmark functions.	33-bus, 69-bus, and 85-bus distribution systems.

(Continues)

TABLE 5 (Continued)

Author, Year [Ref]	Optimization Approach/ Algorithm	Contributions	Objective(s) / DG Type	Basic Principle/ Objective Function	Advantages/Merits	Demerits	Network
Mahmoud et al, 2015,[83]	Analytical approach	The relative loss reduction between every two cases is evaluated for system stability improvement with respect to DG units.	Minimization of power loss/ Conventional	Stability index criteria	Analysis of power loss reduction and voltage profile improvement is carried for different DG units.	Requires more time for computation. Not suitable for complex optimization problems.	33-bus and 69-bus distribution systems.
Atwa et al, 2010,[84]	Probabilistic-based planning approach	The method is to determine the optimal mix of various DG units to minimize system's annual energy loss.	Minimization of energy loss/ Renewable	The objective function is to minimize the system's annual energy loss. The objective function is formulated as MINLP.	The method guarantees the optimal allocation of renewable-based DG for all possible conditions without violating the system constraints.	Less accurate when the high-quality solution is needed.	A typical 42-bus rural distribution system.

TABLE 6 Gradual evolution in DSTATCOM allocation techniques

Author, Year [Ref]	Optimization Approach/Algorithm	Objective(s)	Specific Contributions	Advantages/Merits	Demerits	Network
Hussain and Subbaramiah, 2013,[86]	Analytical approach	Minimization of losses and voltage profile enhancement	The optimal DSTATCOM size is calculated and modeled by maintaining the voltage magnitude as 1 p. u.	The process is simple. Applicable for small systems.	No guarantee of convergence. Not suitable for large systems in terms of computation.	33-bus distribution system.
Farhoodnea et al, 2013,[87]	Firefly algorithm	Average voltage deviation, THD, and total investment cost	The algorithm is based on behavior of fireflies in nature. The algorithm works on two aspects namely light intensity and attractiveness.	The algorithm has reduced average voltage THD and improved voltage profile even at 10% of voltage sag.	Requires parameter tuning and a greater number of iterations for convergence.	16-bus distribution system.
Taher and Afsari, 2014,[88]	Immune algorithm	Minimization of losses, current, and voltage profile enhancement	The method is inspired from biological behavior of the immune system. This algorithm is used to identify both location and size of DSTATCOM.	The algorithm is suitable for distribution systems with variable load levels.	Requires a greater number of parameters tuning. Algorithm is suffering from premature convergence.	33-bus and 69-bus distribution systems.
Yuvaraj et al, 2015,[89]	HSA	Minimization of total network power loss	The algorithm is developed based on the conceptual musical process of obtaining a perfect state of harmony.	Derivative-free optimization process. Applicable for large systems.	Performance of optimization technique in terms of convergence characteristics not been discussed. Requires a greater number of parameters tuning.	33-bus distribution system.
Yuvaraj et al, 2015,[90]	BA	Minimization of power loss	The algorithm is based on echolocation and food search behavior of bats.	Requires less parameter tuning. Stochastic behavior of the loads has been modeled. Reliability of the system is maintained.	Requires more computational time.	33-bus and 69-bus distribution systems.

(Continues)

TABLE 6 (Continued)

Author, Year [Ref]	Optimization Approach/Algorithm	Objective(s)	Specific Contributions	Advantages/Merits	Demerits	Network
Gupta and Kumar, 2016,[91]	Sensitivity approach	Minimization of losses and voltage profile enhancement	The optimal allocation of DSTATCOM in distribution system with seasonal load variation is solved using sensitivity analysis.	The method has achieved reduction in overall network cost with improved voltage profile and reduced power loss.	No guarantee of convergence. Not suitable for large systems in terms of computation.	UK 38-bus practical mesh distribution system.

TABLE 7 Impacts of reconfiguration, capacitor, DG, and DSTATCOM allocation techniques

Impacts on Techniques	Network Reconfiguration	Capacitor Allocation	DG Allocation	DSTATCOM Allocation
Voltage support	✓	✓	✓	✓
Loss minimization	✓	✓	✓	✓
Cost saving		✓	✓	✓
Reliability	✓	✓		✓
Load balancing			✓	✓
THD reduction				✓
Demand side management	✓		✓	✓
Affects protection system coordination	✓		✓	
Green energy			✓	

3.1 | Simultaneous reconfiguration and capacitor allocation

The research publications which are related to loss minimization in distribution networks by simultaneous reconfiguration and capacitor allocation are presented in this subsection. The loss minimization techniques that have been implemented on distribution systems through simultaneous reconfiguration and capacitor allocation are summarized in **Table** 8. So, it can be observed from the literature that only a few researchers have opted simultaneous reconfiguration and capacitor allocation technique for loss minimization.

3.2 | Simultaneous reconfiguration and DG allocation

Recent works on simultaneous reconfiguration and DG allocation for loss minimization in distribution networks are presented in this subsection. Most researchers have considered the basic objective function (loss minimization) for the network reconfiguration problem in distribution systems. The power loss existed in the distribution network can be minimized using two techniques: reconfiguration and DG allocation. Although these techniques have the capability of loss reduction, their simultaneous combination and implementation through analysis will improve the system performance tremendously. However, simultaneous reconfiguration and DG allocation have included additional objectives due to the fact that researchers have different approaches in methodology and implementation. These objectives include cost minimization of active power generated by the companies and DG units, reduction in incorporation cost of the DG to the system, reduction in the system reliability cost, minimization of system operation cost, system power quality improvement, load balancing and elimination of overload condition, minimization of switching time, system reliability enhancement under normal and island conditions, bus voltage deviation enhancement, and emission reduction. Recent works on network reconfiguration with DG allocation for loss minimization in distribution systems are summarized in **Table** 9.

3.3 | DG and DSTATCOM allocation

The research publications which are related to loss minimization in distribution networks through simultaneous DG and DSTATCOM allocation are presented in this subsection. It is observed from Table 7 that the maximum potential benefits can be obtained through optimal allocation of DG and DSTATOM units simultaneously in distribution networks.

Simultaneous DG and DSTATCOM allocation in a distribution system is also a complex combinatorial constrained optimization problem; several researchers have proposed various methods for solving this optimization problem as summarized in **Table** 10.

TABLE 8 Simultaneous reconfiguration and capacitor allocation techniques

Author, Year [Ref]	Optimization Approach/Algorithm	Objective(s)	Specific Contributions	Advantages/Merits	Demerits	Network
Oliveira et al, 2010,[92]	MINLP approach	Minimization of energy losses	The primal-dual interior point method and Lagrange multipliers are used to solve the optimization problem at each step and to evaluate a new sensitivity index for system reconfiguration, respectively.	Requires less computational effort due to reduction in number of optimal power flow simulations. Applicable to large systems with more than one load level.	Less accurate when the high-quality solution is needed.	16-bus, 33-bus, and TPC 83-bus distribution systems.
Kasaei and Godamkar, 2010,[93]	Ant colony optimization (ACO) algorithm	Minimization of power loss	The method is based on ant colonies searching, finding, and carrying food to their nests.	Power loss reduction and voltage profile enhancement have achieved.	Convergence characteristics not been discussed. Lack of results comparison.	33-bus distribution system.
Guimaraes et al, 2010,[94]	Dedicated GA	Minimization of power loss	Unlike the traditional GA, this method uses only one chromosome to store all the information.	Requires less computational effort. The method avoids the generation of the nonradial configuration.	Convergence characteristics not been discussed. Results obtained are not compared.	69-bus and realistic 135-bus distribution systems.
R. Srinivasa Rao, 2010,[95]	HSA	Minimization of power loss	The algorithm is developed based on the conceptual musical process of obtaining a perfect state of harmony.	No derivatives required for the optimization process. Suitable for large systems. Less parameter tuning.	An extensive search has to be carried out for obtaining the global optimal solution.	16-bus and 33-bus distribution systems.
Farahani et al, 2012,[96]	Discrete GA	Minimization of energy losses	Reconfiguration method presented here is based on a simple branch exchange method. The sequence of loops has to be selected for achieving minimum loss.	It reduced the total cost due to capacitor allocation and energy losses.	Convergence characteristics not been discussed. Requires more time for computation.	Real-life 77-bus distribution system.

(Continues)

TABLE 8 (Continued)

Author, Year [Ref]	Optimization Approach/Algorithm	Objective(s)	Specific Contributions	Advantages/Merits	Demerits	Network
Sedighizadeh et al, 2014,[97]	Binary PSO	Minimization of power loss	The method has used binary strings model for representing the states of network switches and capacitors.	The method has reduced the cost of energy losses and emission through simultaneous reconfiguration and capacitor allocation.	The size of capacitors considered are multiples of 300 which lead to high capacitor costs.	16-bus and 33-bus distribution systems.
Sultana and Roy, 2016,[98]	OKH algorithm	Minimization of power loss	The method is a mix of krill herd optimization and oppositional-based learning concept for improving convergence speed.	The method is capable of reducing power loss in constant current, power, and impedance load types.	Computational efficiency has not been discussed. Requires parameters tuning.	33-bus and 69-bus distribution systems.
Gutiérrez-Alcaraz and Tovar-Hernández, 2017,[99]	Two-stage heuristic method	Minimization of electricity losses	The method initially determines the feasible reconfiguration sets up to 10 in number and ranks it based on electrical losses. Later capacitors are placed on these feasible sets to obtain minimum electrical losses, and it is considered as the optimal reconfiguration.	The rank-based methodology has been used for obtaining minimum electrical losses. The algorithm has reduced computational burden by using loss reduction threshold of 1 kW for stopping the process of capacitor switching.	Convergence characteristics not been discussed. The size of capacitors considered is multiples of 300 which lead to high capacitor costs.	12-bus, 16-bus, and TPC 83-bus distribution systems.
Esmaeilian and Fadaeinedjad, 2015,[100]	Binary gravitational search algorithm (BGSA)	Minimization of energy losses and enhance the system reliability	The method utilizes BGSA for solving fuzzy MOOP efficiently. The harmonic power flow is evaluated in the presence of nonlinear loads and shunt capacitor by using a fast harmonic analysis method. To assess the	Requires less computational time. Suitable for large distribution systems.	Convergence characteristics not been discussed.	33-bus and TPC 83-bus distribution systems.

(Continues)

TABLE 8 (Continued)

Author, Year [Ref]	Optimization Approach/Algorithm	Objective(s)	Specific Contributions	Advantages/Merits	Demerits	Network
			system reliability, a state enumeration method has been used which is based on Weibull-Markov stochastic models.			
Sayadi, 2016,[101]	Perturbation PSO	Minimizing the cost of real power losses and capacitor installation	The method designs perturbation module which controls the exploration and exploitation searching of the algorithm to avoid premature convergence.	The algorithm has achieved reduction in cost of real power losses and capacitor installation. In addition, harmonic distortion is considered as suitable criterion for power quality improvement.	Computational efficiency of the algorithm has not been discussed. The obtained minimum bus voltages less than compared methods.	33-bus and Sirjan 77-bus distribution systems.
Home-Ortiz et al, 2019,[102]	Mixed-integer second-order cone programming	Minimizing cost of overall investment and energy losses	The method guarantees the convergence to optimality. For representing the operation of the capacitors and loads, voltage-dependent models are considered instead for constant power models.	Suitable for large systems to obtain good-quality solution. The combinatorial search space of the problem is reduced by reducing the number of candidate buses for capacitor installation.	Computational efficiency of the algorithm has not been discussed. The results obtained are not compared with existing literature.	69-bus and real-time 2313-bus distribution systems.

TABLE 9 Simultaneous reconfiguration and DG allocation techniques

Author, Year [Ref]	Optimization Approach/Algorithm	Objective(s)	Specific Contributions	Advantages/Merits	Demerits	Network
Rosseti et al, 2013,[103]	Heuristic algorithm based on sensitivity indexes	Minimization of energy losses	DG allocation is carried out by conventional power flow solution.	The method has considered constructing a new branch for connecting DG unit to the system.	Computational time taken per iteration is high.	16-bus, 33-bus, and TPC 83-bus distribution systems.
Rao et al, 2013,[104]	HSA	Minimization of power loss	The method has used sensitivity analysis for candidate bus location and HSA for open switches.	No derivatives required for the optimization process. Suitable for large systems. Less parameter tuning.	An extensive search has to be carried out for obtaining the global optimal solution.	33-bus and 69-bus distribution systems.
Taher and Karimi, 2014,[105]	GA	Minimization of power loss	The method is applied to balanced and unbalanced distribution networks for loss minimization.	Obtained power loss saving in unbalanced distribution system through network reconfiguration and DG allocation.	Requires high computational time. An extensive search has to be carried out for obtaining global optimal solution in large systems.	33-bus, 69-bus distribution systems, and unbalanced 25-bus distribution system.
Mohamed Imran et al, 2014,[106]	FWA	Minimization of power loss	The method is based on the fireworks explosion process which is a searching algorithm used to identify the best location of sparks. Voltage stability index (VSI) for pre-identification of candidate bus location.	Minimization of power loss and voltage deviation is obtained in varying load conditions. Suitable for large systems.	Parameter tuning is needed. The solution obtained is near optimum or optimal solution.	33-bus and 69-bus distribution systems.
Esmaeilian and Fadaeinedjad, 2015,[107]	GA with the improved switch-exchange method	Minimization of energy loss	The algorithm has used improved switch-exchange method for network reconfiguration and GA for DG installation.	Requires short runtime. Simultaneous reconfiguration and DG installation are performed on time-varying different types of load.	The solution obtained is near optimal. The solution depends on the parameter values.	33-bus, unbalanced 33-bus, and TPC 83-bus distribution systems.

(Continues)

TABLE 9 (Continued)

Author, Year [Ref]	Optimization Approach/Algorithm	Objective(s)	Specific Contributions	Advantages/Merits	Demerits	Network
Lotfipour and Afrakhate, 2016,[108]	Discrete TLBO algorithm	Minimization of power loss	The method is converted to discrete since network reconfiguration is a discrete optimization problem.	The algorithm can be applied in a smart grid environment and practical applications.	Convergence characteristics not been discussed.	33-bus, 69-bus, and Iranian 59-bus distribution systems.
Nguyen et al, 2016,[109]	Adaptive CSA	Minimization of active power loss	Graph theory is used to reduce the search space with minimum configurations at each stage of the optimization process.	The algorithm has achieved the minimum power and enhanced VSI.	Requires high computational time since number of iterations are more.	33-bus, 69-bus, and 119-bus distribution systems.
Bayat et al, 2016,[110]	Heuristic method	Minimization of power loss	Uniform voltage distribution based constructive reconfiguration algorithm is used for simultaneous reconfiguration and DG installation.	Requires less computational time. Suitable for large systems.	Convergence characteristics not been discussed.	33-bus, 69-bus, and real 136-bus distribution systems.
Esmaeili et al, 2016,[111]	Big bang-big crunch (BBBC) algorithm	Minimization of power loss	The load uncertainties are considered and modeled using triangular fuzzy number technique.	Techno-economic and environmental benefits achieved are a reduction in power loss, operation cost, pollutants emission, and improved VSI.	Parameter tuning is needed.	Balanced 33-bus, 25-bus, and unbalanced 25- bus distribution systems.
Jasthi and Das, 2017,[112]	Heuristic cum analytical algorithm	Minimization of active power loss	The analytical approach used for DG installation and heuristic method for network reconfiguration is based on exact loss formula.	The unique feature of this approach is it does not require a load flow solution. The same approach is extended further to multi-objective with weighted sum technique.	Requires high computational time.	33-bus, 69-bus, 85-bus, and 136-bus distribution systems.

(Continues)

TABLE 9 (Continued)

Author, Year [Ref]	Optimization Approach/Algorithm	Objective(s)	Specific Contributions	Advantages/Merits	Demerits	Network
Hamida et al, 2018,[113]	Evolutionary technique	Minimization of active power loss	Renewable-based DG uncertainties have modeled and installed at optimal locations.	Techno-economic and environmental benefits achieved are a reduction in power loss, annual operation (installation and maintenance) cost, and pollutants emission.	Feasibility of technique for large systems not discussed.	33-bus distribution system.
Sambaiah et al, 2019,[114]	Salp swarm algorithm (SSA)	Minimization of power loss	The algorithm is based on the swarm behavior of salps in deep oceans. The optimal food location is considered as the optimal solution.	Requires less computational time. Suitable for large systems. Less parameter tuning required.	Results obtained are based on random generation of variables.	33-bus and 69-bus distribution systems.
Dogan and Alci, 2019,[115]	ABC, DE, PSO, GA	Minimization of real power loss	LSF is used to predetermine the location for DG. Four algorithms are implemented for simultaneous reconfiguration and DG allocation in distribution system with different load levels.	Minimization of power loss and voltage deviation is obtained in varying load conditions. Suitable for large systems.	The algorithms are producing identical results.	69-bus distribution system.

TABLE 10 Simultaneous DG and DSTATCOM allocation techniques

Author, Year [Ref]	Optimization Approach/Algorithm	Objective(s)	Specific Contributions	Advantages/Merits	Demerits	Network
Devi and Geethanjali, 2014,[116]	PSO	Minimization of line losses	The method is based on swarming behavior with simple mathematical equations. The concepts of DG and DSTATCOM allocation in distribution networks are well discussed.	The algorithm is suitable for placement of both DG and DSTATCOM in distribution systems.	Convergence characteristics not been discussed. Requires a greater number of parameters tuning.	12-bus, 34-bus, and 69-bus radial distribution systems.
Devabalaji and Ravi, 2016,[117]	BFOA	Minimization of power loss	LSF analysis method is used to predetermine candidate bus location and BFOA is used for the optimal size of DG and DSTATCOM on the distribution system with different load levels.	The algorithm has achieved maximum system benefits along with loss minimization and voltage profile enhancement.	Convergence characteristics not been discussed. Parameter tuning is needed.	33-bus and 119-bus distribution systems.
Thangaraj and Kuppan, 2017,[118]	Lighting search algorithm	Minimization of power loss	The algorithm is based on the lighting phenomenon mainly depend on transition, space, and lead projectile. Optimal allocation of DG and DSTATCOM on the distribution system with different load levels are discussed.	The algorithm has achieved reduced power loss, voltage deviation, and improved voltage stability.	Computational efficiency of the algorithm has not been discussed. Parameter tuning is needed.	33-bus and 69-bus distribution systems.
Iqbal, 2017,[119]	Analytical approach	Minimization of losses	A direct load flow method along with LSF analysis method is used to predetermine candidate bus location.	The method is simple and suitable for placement of both DG and DSTATCOM in distribution systems.	Feasibility of technique for large systems not discussed.	33-bus distribution system.

(Continues)

TABLE 10 (Continued)

Author, Year [Ref]	Optimization Approach/Algorithm	Objective(s)	Specific Contributions	Advantages/Merits	Demerits	Network
Singh and Yadav, 2018,[120]	GA	Minimization of total real power loss	The optimal location and size of both DG and DSTATCOM are identified under varying load conditions on the distribution system.	Computationally simple and robust search in complex problem spaces.	Convergence characteristics not been discussed.	75-bus test system.
Sannigrahi and Acharjee, 2018,[121]	Root tree optimization algorithm	Minimization of power loss	The algorithm is based on nature of root growth in trees.	The algorithm has achieved maximum system benefits along with loss minimization and voltage profile enhancement.	Computational efficiency of the algorithm is not been discussed. Feasibility of technique for large systems not discussed.	33-bus distribution system.
Yuvaraj and Ravi, 2018,[122]	CSA	Minimization of power loss	The algorithm is based on obligate brood parasitism of some species of a cuckoo which uses other host birds' nests for laying eggs.	The algorithm requires less parameter tuning.	The method is computationally expensive. The algorithm is suffering from premature convergence.	33-bus and 136-bus distribution systems.

3.4 | Simultaneous reconfiguration, capacitor, and DG allocation

In recent years, most of the research work has been carried out on both simultaneous reconfiguration and capacitor allocation and simultaneous reconfiguration and DG allocation for solving loss minimization problem in distribution systems. Although previous techniques have the capability of loss reduction, the trend has been started to achieve maximum loss reduction and voltage profile improvement through simultaneous reconfiguration, capacitor, and DG allocation from the past few years. However, only a few researchers have investigated and implemented various techniques for performing simultaneous reconfiguration, capacitor, and DG allocation on distribution systems. The research publications which are related to the abovementioned techniques are presented in this subsection. The loss minimization techniques that have been implemented on distribution systems through simultaneous reconfiguration, capacitor, and DG allocation are summarized in **Table** 11.

In the next section, the impact of simultaneous reconfiguration, capacitor, DG, and DSTATCOM allocation on power loss and voltage profile and various methodologies has been discussed.

4 | DISCUSSIONS

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 network reconfiguration, capacitor, DG, and DSTATCOM allocation techniques in distribution networks. 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. However, the trend has been created by several researchers to allocate DSTATCOM in distribution network for solving power quality problems. Some noticeable points made in this review are discussed below:

4.1 | The impact of reconfiguration, capacitor, DG, and DSTATCOM allocation on power losses

Several researchers have various approaches for solving power loss minimization problem in distribution networks which differ from each other in terms of implementation and methodology. It is observed from the literature that in addition to basic objective function of network power loss some more objectives included in the optimization problem are: minimizing the cost of active and reactive power generated by the DISCOMs, minimizing the cost of active and reactive power generated by capacitor and DG units in the system, cost reduction in incorporation cost of capacitor and DG to the system, reduction in the system reliability cost, minimization of system operation and maintenance cost, system power quality improvement, maintaining load balance and elimination of overload condition in feeders, minimization of switching time, system reliability enhancement under normal and island conditions, bus voltage deviation enhancement, and emission reduction.

The network power losses incurred in the system can be minimized using the following techniques: network reconfiguration, capacitor, DG, and DSTATCOM allocation individually. Although these techniques are capable of power loss minimization, their simultaneous combination and implementation will improve the system performance tremendously. Thus, the concept of simultaneous network reconfiguration, capacitor, DG, and DSTATCOM allocation has produced better results compared with the solo approach. In addition, the simultaneous technique will enhance the search speed and avoids the local optima.

4.2 | The impact of reconfiguration, capacitor, DG, and DSTATCOM allocation on voltage profile

Capacitor allocation techniques are normally used in the distribution network for loss reduction and voltage profile enhancement. Initially, researchers choose to solve the capacitor allocation problem without reconfiguration, which will

TABLE 11 Simultaneous reconfiguration, capacitor and DG allocation techniques

Author, Year [Ref]	Optimization Approach/Algorithm	Objective(s)	Specific Contributions	Advantages/Merits	Demerits	Network
D. Q. Hung et al, 2013,[123]	Combined analytical approach	Minimization of power loss	Elgerd's loss formula is used for loss calculation. The authors used a combination of reconfiguration, capacitor, and DG installation for obtaining high loss reduction.	The method is applied for both standard and real-time test systems with varying load conditions. The maximum installation of capacitor and DG units will maximize the loss reduction.	The cost associated with capacitor and DG installation not been discussed.	33-bus and real 687-bus distribution systems.
Gallano et al, 2014,[124]	Non-dominated sorting genetic algorithm (NSGA-II)	Minimization of power loss	NSGA-II is used to obtain various system configurations, and fuzzy decision-making analysis is used for identifying optimal system configuration.	Minimizes power loss and line loading and enhances voltage stability. This method is considered as the robust method for solving the various complex multi-objective optimization problem.	The cost associated with capacitor and DG installation not been discussed. Parameter tuning is needed.	69-bus distribution system.
Saonerkar and Bagde, 2014,[125]	GA	Minimization of power total loss	The method is traditional GA which uses mutation and cross-over operators for identifying a number of capacitors and DG and VSI for pre-identification of corresponding candidate bus locations.	The method is inspired by nature of evolution. Less parameter tuning and feasible for a large system.	Convergence characteristics not been discussed. The solution obtained is near optimal. The solution depends on the parameter values.	33-bus distribution system
Kanwar et al, 2015,[126]	Improved PSO, GA, and Cat swarm optimization (CSO) algorithms.	Minimization of annual energy loss	Among the three methods used, one is evolutionary and two are swarm intelligence-based algorithms. The	The convergence characteristics are well illustrated. Suitable for complex and large systems with solution guarantee.	The cost associated with capacitor and DG installation and operation not been discussed.	33-bus and 69-bus distribution systems.

(Continues)

TABLE 11 (Continued)

Author, Year [Ref]	Optimization Approach/Algorithm	Objective(s)	Specific Contributions	Advantages/Merits	Demerits	Network
			voltage constraints are satisfied through penalty factor method.			
Tolabi et al, 2015,[127]	Fuzzy-ACO algorithm	Minimization of power loss	The method is based on ant colonies searching, finding and carrying food to their nests; this algorithm is used to obtaining various system configurations and fuzzy decision-making analysis is used for identifying optimal system configuration.	The method has achieved a significant reduction in power loss, line loading, and improvement in voltage profile. Suitable for complex and large systems.	The cost associated with capacitor and DG installation and operation not been discussed. The solution depends on the parameter values.	33-bus and TPC 83-bus distribution systems.
Mohammadi et al, 2017,[128]	BFOA	Minimization of power loss	The method is based on the group foraging behavior of bacteria; this algorithm is used to obtaining various system configurations, and fuzzy decision-making analysis is used for identifying optimal system configuration.	The method is well-suited for combinatorial optimization problems. It can be used for fast restoration service in DAS and time varying loads.	Tuning of parameters and premature convergence are two problems. Feasibility of technique for large systems not discussed.	33-bus and 69-bus distribution systems.
Rugthaicharoencheep et al, 2018,[129]	GA	Minimization of system power loss	The method is a combination of GA and a search algorithm based on mechanics of natural selection and genetics is used to obtain the optimal configuration pattern.	Minimum power loss is obtained without voltage limits violation.	The cost associated with capacitor and DG installation and operation not been discussed.	33-bus distribution system.

(Continues)

TABLE 11 (Continued)

Author, Year [Ref]	Optimization Approach/Algorithm	Objective(s)	Specific Contributions	Advantages/Merits	Demerits	Network
Ganesh and Kanimozhi, 2018,[130]	Modified FPA	Minimization of power loss	VSI is used for pre-identification of most candidate bus locations for capacitor and DG installations.	The method is well-suited for combinatorial optimization problems. The analysis is carried on three different load levels.	Values of weights are not been defined. Results are self-compared.	33-bus, 69-bus, and 118-bus distribution systems.
Montoya et al, 2014,[131]	GA and minimal spanning tree	Minimization of active power loss	The reconfiguration problem is solved by using a deterministic algorithm (Kruskal algorithm). The renewable-based DG units used for installation are solar PV and wind turbines.	To maintain minimum bus voltage value within the limits a penalty function is used.	Computational efficiency of the algorithm has not been discussed. The results obtained are not compared with existing literature.	33-bus distribution system
Muthukumar et al, 2016,[132]	HSA and particle ABC algorithm	Minimization of power loss, line loading, and improvement of voltage profile	The method is a hybrid approach, which integrates HSA exploration ability and particle ABC algorithm exploitation ability for obtaining full potency.	The solution quality is tested by using box plot and Wilcoxon rank sum tests.	The algorithm is suffering from premature convergence.	69-bus and 118-bus distribution systems.
Pawar et al, 2016,[133]	HSA	Minimization of system losses	The algorithm is developed based on the conceptual musical process of obtaining a perfect state of harmony.	No derivatives required for the optimization process. Suitable for large systems. Less parameter tuning.	An extensive search has to be carried out for obtaining the global optimal solution.	33-bus distribution system
Ameli et al, 2017,[134]	HSA and ACO algorithm	Minimization of loss	A dynamic method is used for simultaneous reconfiguration and capacitor allocation in the presence of DG units with uncertainties in	HSA is used as case reduction, and ACO is used for the optimal path for cost minimization.	Load uncertainties are not considered. Convergence characteristics not been discussed.	118-bus distribution system

(Continues)

TABLE 11 (Continued)

Author, Year [Ref]	Optimization Approach/Algorithm	Objective(s)	Specific Contributions	Advantages/Merits	Demerits	Network
			generation overtime. The computational burden of the method is reduced by using case reduction technique.			
Biswas et al, 2018,[135]	Success history-based parameter adaption technique of DE	Minimization of real power loss	In this method, linear population size is used for improving exploration capability during initial search stage.	The control parameters used in this method provide algorithm to explore vastly.	Requires high computational time. An extensive search has to be carried out for obtaining global optimal solution in large systems.	33-bus and 69-bus distribution systems.

provide reactive power compensation. Reconfiguration is performed by closing the tie-switches and opening the sectionalizing switches of the network. Generally, closing the tie-switch yield transfers the voltage between feeders, while opening the appropriate sectionalizing switch reduces the active power loss. As a result of reconfiguration, the voltage will be balanced and will have subsequent improvement in its profile. Since DG is distinct in the distribution network, several researchers choose to solve DG allocation problem without reconfiguration for loss reduction in their respective work. It is observed that in all cases, network power loss is considered as the critical issues that the majority of the researchers are trying to solve. Optimizing the sizes of capacitor and DG is vital in avoiding any negative effects on the network. Network reconfiguration, capacitor, and DG allocation and simultaneous DG and DSTATCOM allocation share the power loss minimization objective. Works focused on simultaneous reconfiguration, capacitor, and DG allocation in the distribution network showed their capability of power loss reduction, thereby network performance and efficiency can be improved.

4.3 | Various methodologies for reconfiguration, capacitor, DG, and DSTATCOM allocation problem

This article reports a comprehensive review of the currently available methodologies on reconfiguration, capacitor allocation, DG allocation, simultaneous reconfiguration and capacitor allocation, simultaneous reconfiguration, and DG

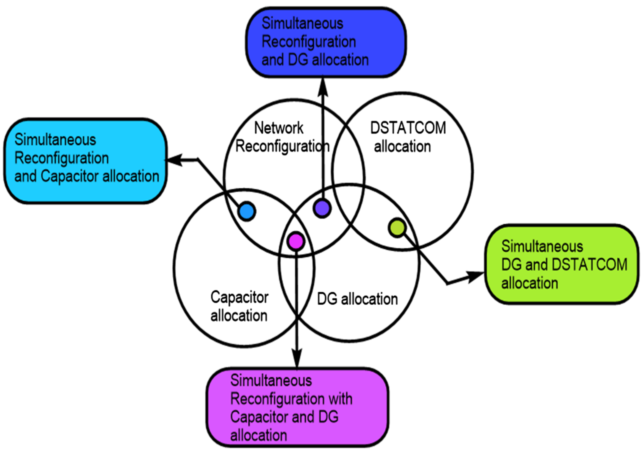

FIGURE 2 Loss minimization techniques for optimal planning and operation of distribution systems

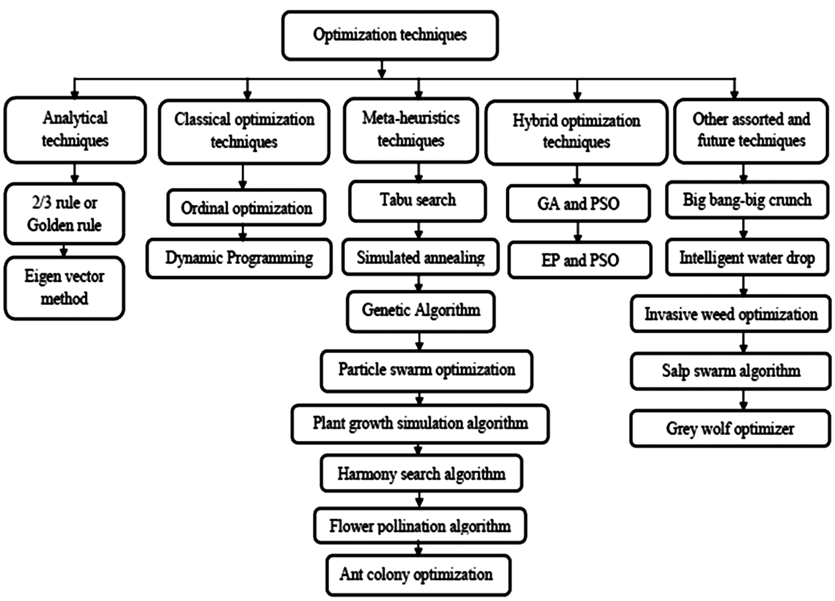

FIGURE 3 Optimization techniques for network reconfiguration, capacitor allocation, and DG allocation

allocation, simultaneous DG and DSTATCOM allocation, and simultaneous reconfiguration, capacitor, and DG allocation. **Figure 2** shows the loss minimization techniques used for optimal planning and operation of distribution systems. The methodologies implemented to solve these aforementioned techniques are presented in **Figure 3** divided into five categories:

i. Analytical techniques
ii. Classical optimization techniques
iii. Meta-heuristic (artificial intelligence) techniques
iv. Hybrid optimization techniques
v. Other assorted and future techniques

In the last section, the concluding remarks are presented.

5 | CONCLUSION

This article provides a comprehensive overview of the state-of-the-art techniques for solving distribution network loss minimization problem through network reconfiguration, capacitor, DG, and DSTATCOM allocation. It looks at the widespread methodologies used in distribution network reconfiguration, capacitor, DG, and DSTATCOM allocation with a profound review of relevant background, the current status, and realistic requirements. It is based on several research articles published over the past four decades to summarize the comprehensive progressive research in this field. The citations presented in this article serve as a representative sample of currently available technical assessments relating to the distribution system performance enhancement by achieving loss minimization and voltage profile enhancement. Since the power system continues to evolve, it is useful to update survey periodically on this topic. In this survey, many methods have been used to solve the problem as single and multi-objective with various constraints. Various techniques discussed in the literature for distribution system loss minimization are leading to the following conclusions:

i. Network reconfiguration is the most economical technique in low voltage distribution networks. However, it requires a complicated control strategy, and also it involves several switching combinations which makes it a complex optimization problem. Although this technique is efficient, it has a limited payback.
ii. Capacitor allocation is most suitable in high voltage distribution networks which is a simple and reliable technique. However, this technique has limited advantages apart from loss minimization.
iii. DG allocation is more attentive on integrating existing small generations (for instance, when isolated small photovoltaic plants or wind farms penetrate the distribution system), which is most efficient. However, it requires effective techniques for implementation and installation of this method is least reliable.
iv. DSTATCOM allocation in distribution network receives more attention due to its various advantages over conventional capacitor allocation. However, it requires effective techniques for implementation, installation, and control strategy of DSTATCOM.

Among these methods present in the literature, the simultaneous techniques seem to be the most efficient approach for system performance enhancement due to the aforementioned advantages. Furthermore, the trend has been created to install both DG and DSTATCOM simultaneously in distribution networks for achieving maximum potential benefits of the system. In near future, solving simultaneous reconfiguration with DG and DSTATCOM allocation problem in distribution networks will achieve more attention from both DNO and researchers in this field.

NOMENCLATURE

S	savings ($)
R	line resistance in per unit (pu)
X	line reactance in pu
J	branch complex current
kVAR	kilo-volt ampere reactive

kW	kilo-watt
kV	kilo-volt
R_e	impedance real part
P_b,Q_b	active and reactive power flow in the branch
$P_{T,loss}$	total power loss
r_{ij}	resistance of line connected between bus i to j
V_D	voltage deviation
i_{cb}	capacitor bank sizes installed at node b
K_p	constant to convert peak power losses to dollars
K_e	constant to convert energy losses to dollars
K_c	annual cost of reactive power injected per unit ($/kVAR/year)
LP	reduction in peak power losses
LE	reduction in energy losses
CC	overall capacitor cost
K_{cf}	fixed capacitor cost
T_j	operation time duration of j^{th} load level
P_{DG}	DG active power
W	weighting factor
E	total active loss
α_1,α_2 *and* α_3	weighting factors ($\alpha_1+\alpha_2+\alpha_3 = 1.0$)
Z_b	branch impedance
BGSA	binary gravitational search algorithm
BBBC	big bang-big crunch
SSA	salp swarm algorithm
NSGA-II	non-dominated sorting genetic algorithm
T&D	transmission and distribution
KEPC	Korean electric power corporation
TPC	Taiwan power company
SA	simulated annealing
MIHDE	mixed-integer hybrid differential evolution
ACO	ant colony optimization
PGSA	plant growth simulation algorithm
PSO	particle swarm optimization
DP	dynamic programming
GA	genetic algorithm
TS	tabu search
TLBO	teaching and learning-based algorithm
BA	bat algorithm
BFOA	bacteria foraging optimization algorithm
CSA	cuckoo search algorithm
SSO	shark smell optimization
WOA	whale optimization algorithm
FPA	flower pollination algorithm
FWA	firework algorithm
ABC	artificial bee colony
OKH	oppositional krill herd
GWO	grey wolf optimizer
IWD	intelligent water drop
IWO	invasive weed optimization
ALO	antlion optimization
EP	evolutionary programming
SOS	symbiotic organisms search

HSA harmony search algorithm
CSO cat swarm optimization

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ORCID

Kola Sampangi Sambaiah https://orcid.org/0000-0001-9023-1918

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