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Paper

Multi-objective Optimization of Optimal Placement and Sizing of Distributed Generators in Distribution Networks

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Due to the growing attention for the environmental impacts and power loss minimization, distributed generators (DGs) have been introduced widely into the electric power system. One of the challenges of integrating with the power system is to determine their optimal placement and sizing, which, when not respected, adversely affects the performance of the electrical network. In this paper, three multi-objective algorithms of particle swarm optimization (PSO), variable constants (VCPSO) and genetic algorithm (GA) are adopted and implemented. The main objectives are to detect the optimum size and location of multiple DGs aiming to reduce the active power loss and improve bus voltage deviations in the distribution networks. The paper conducts a comprehensive review of the optimal size and location of the DG via systematic procedures, including definition, classifications, technologies of DGs. Then, the performances evaluation of the three optimization methods are presented and compared with other methods. The presented optimization methods are tested on the IEEE-33 bus, 32-line radial distribution network. Four different scenario-based studies including base case and different number of DGs are performed to examine the accuracy of the presented algorithms. The obtained results prove that all the three algorithms are suitable for this multi-objective optimization and VCPSO offers the best solution in terms of convergence and, and it has lowest average computation time. The performance and accuracy of the presented approaches and their improvements in the power loss and bus voltage profile are discussed and presented in detail. The obtained results show that more than 65% of active power loss reduction has been attained with the proper sizing and placement of DG systems.

Keywords: optimal sizing and placement; multi-objective; distributed generation; optimization techniques; variable constant PSO

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1. Introduction

Due to the great and accelerating demand in the requirement on electric energy and with the gradual decay of non-renewable energy sources (fossil fuels and others), the structure of the main electric networks must be expanded to meet the increasing needs for electric energy. The conventional view of electricity structures is huge main power stations offering MW or GW generation of power. Most of the electrical power generation in the world is produced by thermal fossil-fuel stations using alternators. These traditional generators are usually having fixed and inflexible frequency performance due to the rotating inertia of alternators. If a large synchronous generator (MW or GW-scale) is replaced by tens or hundreds of small-scale power plants, the frequency performance becomes weaker due to the decreased system inertia [1]. The control schemes and number of control places will certainly increase and substantially add to the burden of the system operator. New protection systems and arrangements which require new transducers and relays to identify lower current values and advanced protection managements are necessary. Energy flexibility and demand side management resources should be created in the development, operation, and maintenance of infrastructure to enable the integration of these small-scale plants into the grid. In addition, numerous power system assistance tasks, including voltage and frequency control and ride-through by active and/or reactive power regulation.

The critical challenges are finding approaches to use energy sources at adequate costs and in aspects that do not harm the environment. The main challenges are developing approaches to reasonable, reliable, and affordable energy resources while adopting environmental influences at all levels. Strategies can provide sustainable growth by [2]:

- Providing sufficient and reasonable energy resources, including alternative fuels for cooking and electricity for domestic and commercial use to unserved regions.

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- Promising energy proficiency.
- Speed up the use of renewable energies.
- Expanding the distribution and use of other innovative energy technologies.

The use of distributed generators (DG) and its integration to the electrical systems is one of these approaches as an alternate planning option. Distributed generation is the generation of electric power through generators with capacities from few kilowatts to hundred Megawatts, which is directly linked with the electrical distribution system. DG systems technologies involve solar cells, wind energy and fuel cells. DG systems have received a lot of substantial consideration because of their ability to improve the economic and technical characteristics of energy systems and reduce dependence on traditional energy sources [1].

The main interesting preference of distributed generation is that DG systems are dispersed and placed in or near to loads to provide energy with fewer leads and higher efficiency compared to central generating stations with power transmission lines and electrical distribution systems. On the other hand, DGs have a clear influence on the power flow and electrical voltage in the electrical network. This effect may be positive or negative based on the management of the electrical distribution system and the characteristics of the generators used in the distributed generation. Renewable energy DGs provide the electrical network with renewable power from numerous nearby available renewable energy resources such as solar photovoltaics, wind turbines and fuel cells generation systems. The global generated capacity of renewable energy has increased recently, and it is expected to achieve a significant partnership in hybrid generations in the future as illustrated in Fig. 1. Based on the annual renewable energy statistics for 2020 released by International Renewable Energy Agency (IRENA), the most comprehensive, available installations of renewable energy potential point to growing in all regions of the world, although at variable capacities. Renewable energy now accounts for a third of all power capacity installed in all regions of the world and it reached 2537 GW by the end of 2019 [3]. The increase in global renewable capacity during 2019 only is 176 GW with net growth capacity of 54%. Wind power and solar energy are considered the major part and reached 623 and 586 GW, respectively. Additional renewables involved 124 GW of bioenergy, 14 GW of geothermal and 500 MW of marine power (tidal, wave, and ocean power).

The new characteristics of markets with various client's incorporation high integration of renewable and DGs request for developments of the classical power networks. The future power network, specifically smart grid, is intended to cope with the present challenges and to enhance the generation and features of energy production. In fact, there is no clear standards universally, on what a power network should involve converting into the smart grid [4]. The crucial key points are that the smart network still lacks commonly established guidelines which prohibit the incorporation of innovative applications, smart devices and meters, and renewable energy sources and limits the computability between them. Smart grid coordination and communications between energy generation, transmission, distribution, and utilization involve bi-directional communications, computability between enhanced applications and end user reliable and secure communications with low-potentials and adequate bandwidth [5]. Reduction of transmission and distribution losses and power quality to all households are important challenges that should also be ensured

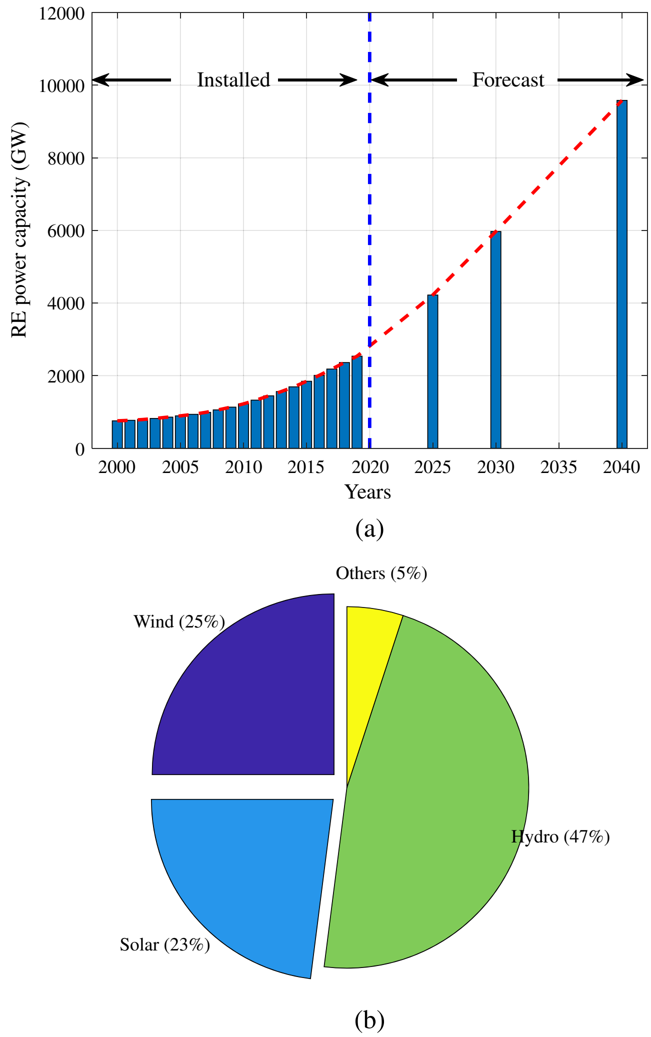

Fig. 1. Renewable Energy generation capacity. (a) Installed capacity progress. (b) Installed capacity in 2019

to fulfill smart grid vision [6]. Improved power quality, better ability of control, higher reliability, and security, uses of demand-side management utilizations, advanced metering structures, integration of renewable energy resources, grid optimization and innovations are the essential features of micro grids (MGs) to accomplish the environmental targets and the economic profits [7].

The most substantial feature of MGs is the high penetration of the DG systems that are dispersed and positioned near to the load center and in the neighborhood to the consumers. The consideration in MGs is receiving more attention as an alternative to large central generation stations owing to its potential improvements to supply secure, reliable, staple, and promising energy from RES [8]. DG systems have been established to efficiently enhance stability of power systems, energy productivity, power quality and environmental impacts [9] and offered several benefits such as:

- Reserve generation to provide power during system outages until service can be restored.
- Peak shaving to decrease the total expense of power by providing power throughout highest load times when the cost of electricity is high.

- Use both electrical energy and heat allowed near the DG for the user, thus increasing the overall energy efficiency.
- Effective loss minimization compared to other ways of reducing losses [10].
- Considerable environmental benefits made possible using low or zero emission systems including solar power, fuel cells and wind energy systems.
- Less influence on the main grid, through good compatibility between generation and demand, regardless of the potential level of generation through alternative energy sources.

Optimal integration of DGs is one of the major challenges in the system design to optimize energy losses and reduce bus voltage drops. Several DGs should be optimized, installed, and effectively synchronized with the existing protection systems. These issues should be addressed prior to selecting DG as a planning option [11].

In this paper, multi-objective algorithms using particle swarm optimization (PSO), variable constants particle swarm optimization (VCPSO) and genetic algorithms (GA) are applied for the multi-objective optimal placement and sizing of DGs system in distribution networks for active power loss optimization and voltage profile improvement. A multi-objective function in terms of power loss index and voltage deviation index based on optimal size and location of multiple DGs is presented. For validation of the effectiveness of the presented methodology, the standard IEEE 33-bus standard radial distribution network is used for inspecting the impacts of integrating DG system.

The main objectives are to detect the optimum size and location of multiple DGs aiming to minimize the active power loss and improve bus voltage profile in the distribution systems. In the first part, the paper conducts a review summary of the optimal size and location of the DG via systematic procedures, including definition, classifications, technologies of DGs. Then, the performances evaluation of the three optimization methods are presented and compared. The presented optimization methods are tested on the IEEE-33 bus, 32-line radial distribution network. Four various scenario-based studies including base case and different number of DGs are performed to examine the performance of the three algorithms. The obtained results prove that the three algorithms were suitable for the optimization of DG placement and sizing. However, VCPSO provides best results in terms of convergence, and it has lowest average computation time. The validation and accuracy of the proposed approaches and their effects in the power loss and bus voltage profile are discussed and presented in detail. The results obtained show that more than 56% improvement in the active power loss has been attained with the proper sizing and placement of DG systems. The obtained results proved that the total active power loss and voltage profile in the distribution network are extremely dependent on the placement and size of the integrated DGs. The integration of optimal size and location of DGs are efficient in terms of decreasing total active and reactive power loss and improving voltage profile, while improper sizing leads to negative impacts.

The remainder of the paper is organized as follows: Section 2 presents a review of literature, involving definition, classifications, technologies of DGs. Problem formulation and optimal power flow are given in Section 3. The multi-objective optimization techniques are illustrated in Section 5. The results and discussions are presented in Section 6. The conclusion and suggested future work are given in Section 7.

2. Literature Review

2.1. Definition of distributed power generation

Distributed Power generation or dispersed generators are one of the significant concepts in power systems and are commonly known as generating sources small enough compared to central power stations [12]. Several definitions of the DG have been suggested by various specialized agencies as Institute of Electrical and Electronic Engineers (IEEE), International Energy Agency (IEA), Electric Power Research Institute (EPRI) and International Council on Large Electric Systems (CIGRE). Many DG classifications are commonly according to the capacity and placement of DG in relation to the central generating plants. According to IEA definition, DG are defined as generation sources supplying a load on-site, giving support to the main grid and are integrated to the network at distribution voltage levels. CIGRE expresses DG as the generation unit that not centrally planned or dispatched, normally integrated to the distribution systems and less than 50–100 MW. Based on the IEEE definition, DGs are generation units smaller than the centralized generating stations in which integration at any location in electrical grid is possible. Some definitions of DG are based on location considering no limitation on the size of the DGs or technology used. EPRI defines DG as dispersed energy sources in the range of few kilowatts up to 50 MW [12] and it forecasted that DG share will be 25% of the newly installations in the year 2025. In another research, Natural Gas Foundation (NGF) have assurance that the share of DGs in the newly installed generation will be 30% [13].

In Ref. [14], the concept of placement of distributed generators differs among authors. Numerous authors identify the placement of DGs at the distribution system, some authors extend the definition to involve the client sides, and some involve the transmission system. Generally, DGs are connected to the distribution system but large offshore wind farms could be connected to the transmission system [15]. A medium and large-sized wind farms are directly integrated to the transmission system, due to the limited capacity of the distribution system [16]. Based on Distributed Power Coalition of America (DPCA), DG systems can be integrated directly to the client side or to transmission or distribution systems [16]. In Ref. [17], the authors override the commonly used definition of DGs and included large wind parks connected to the transmission system and large solar power installations that may appear within a few years' time. In Ref. [15], the authors investigate the influences of DGs on transmission system stability using 39-bus England high voltage transmission system in the northeast of the U.S.A. Standards for definition and classifications of DG systems are given in Fig. 2.

2.2. Distributed generation technologies

Recently, DG technologies have made a significant improvement in the development and applications. Generally, DG technologies involve generation and storage systems that can be categorized by types of fuels and devices and their capability of active and reactive power feedings. DG technologies are essentially classified into renewable and non-renewable energy sources [12]. Conventionally, micro turbine and diesel generators are mechanisms that use the flow of gases to convert thermal energy into mechanical energy. These generators have been considered equivalent to DG systems due to their high operation reliability and cheap price. Diesel, biogas and natural gases are the main fuel used. However, high fuel cost and environmental pollutions make them less preferable as compared

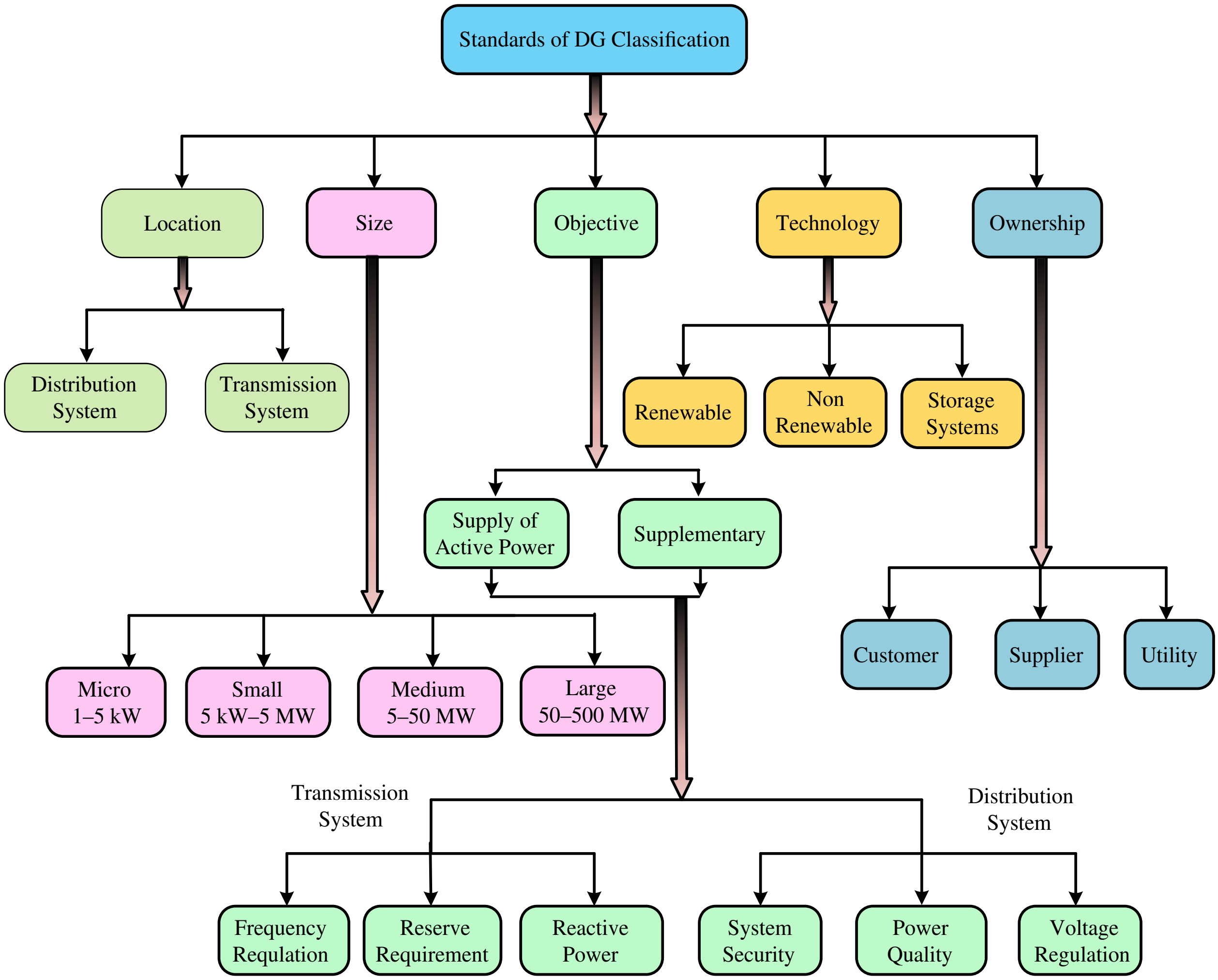

Fig. 2. Standards of DG classifications

to other types of DG systems [18]. Renewable DG systems receive attractive attention for network integration due to its environmental and sustainability concerns. Mostly, PV systems and wind turbines energy conversion are the most renewable technologies at present. Fuel cells are relatively simple electrochemical devices that convert chemical energy directly into electrical energy and they are well suitable for DG applications due to their high efficiency and nearly zero emissions. The types of fuel cells differ according to several factors such as: operating temperature, chemical medium, energy efficiency and durability of the material used. There are five main kinds of fuel cells as proton exchange membrane, solid oxide, molten carbonate, direct methanol and alkaline. Electrical energy storage systems (EESS) as batteries, super capacitors pumped storage and load control strategies are also categorized as part of DG technologies because they are occasionally incorporated in DG units. Renewable DGs are preferable compared to non-renewable units due to high availability in different geographic regions and due to clean technology. Technical performance such as cost, size and efficiency are essential factors in selecting their potential applications. Moreover, hybrid technologies are generally configurated in networks to produce security support and high-level reliability. Figure 3 shows different DG technologies.

2.3. Optimization objectives Many optimization approaches and techniques for selecting optimal allocation and sizing of DGs are introduced and reported in literature and received an attractive attention by authors. Numerous studies have been accomplished to minimize the active power loss, enhancing voltage profile, and increasing power system hosting capacity of the network. Various optimization techniques such as Simulated Annealing (SA), Fuzzy Genetic Systems (FGS), Genetic Algorithm (GA), Differential Evolution (DE), Particle Swarm Optimization (PSO), Ant Lion Optimization Algorithm (ALOA), Genetic Bee Colony (GBC) Algorithm, Gravitational Search Algorithm (GSA), Fuzzy Expert System (FES), Gray Wolf Optimizer (GWO), Artificial Bee Colony (ABC) and many other approaches have been proposed to determine the optimal placement and size of DG systems in the power networks [19,20]. The primary objectives of these methods include voltage stability, minimizing power losses to an adequate level, minimizing voltage deviation, minimizing costs, emission reduction, etc. [5]. Figure 4 depicts the most common DG allocation and sizing objectives. A multi-objective optimization problem based on a Pareto frontier differential evolution algorithm [21], a hybrid method based on the imperialistic competitive algorithm and GA [22], and simplified analytical approaches [23], are presented. An ant lion

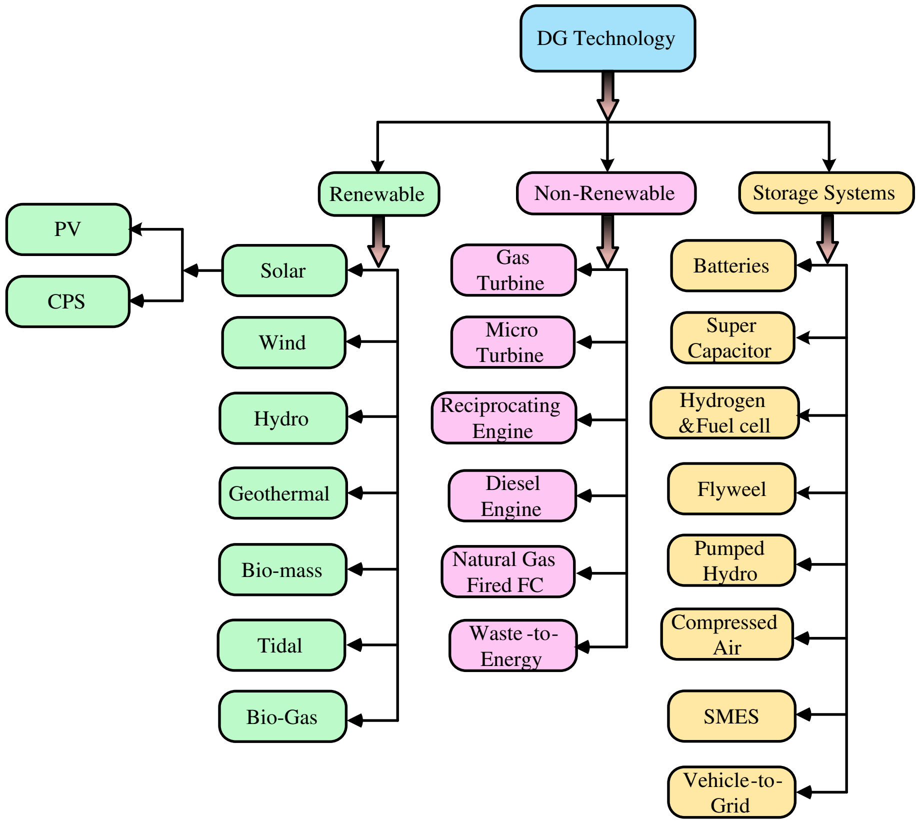

Fig. 3. DG technologies

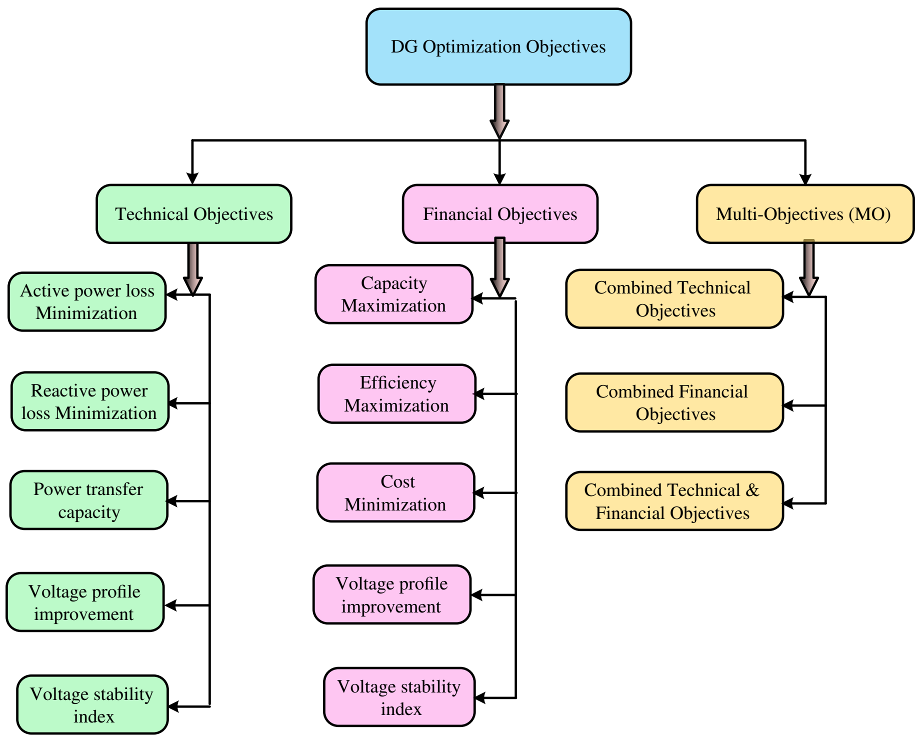

Fig. 4. DG optimization objectives

optimization, such as a novel metaheuristic algorithm [24], are used for placement and sizing of DGs. A continuation power flow and modal analysis [25] and optimal power flow (OPF) algorithm [26], were used to optimal placement and sizing of DGs in the distribution networks.

2.4. Approaches for optimizing location and sizing of DGs

Different approaches for solving the optimization objective of finding the optimal location and sizes of DGs in distribution systems can be categorized into three main types and will be discussed in the following [27]:

2.4.1. Numerical approaches

Numerical approaches are built on the principle of mathematical analysis and programming, the overview of the various numerical approaches is given in the following:

1. Gradient search—this approach is suggested in Ref. [28] and utilized to determine the optimal size of DGs in networks when neglecting the network's short circuit restrictions.
2. Linear programming—this approach is developed in Ref. [29], is used to determine the best site for DGs in the distribution network, with the most permissible installation of DGs.
3. Sequential Quadratic Programming (SQP)—this second-order differential approach, described in Ref. [30], is utilized to determine the best location and size for multiple DGs in distribution systems when neglecting the network's short-circuit limitations.
4. Exhaustive search—It is a multi-objective approach, utilized in Ref. [31] for locating and sizing DGs with an emphasis on improving dependability and minimizing loss under constant and changing load situations. It takes into accounts the performance of renewable energy sources and loads over time.
5. Ordinal optimization—this approach, proposed in Ref. [32], is utilized to determine the best position and size of DGs in the distribution systems, balancing power loss minimization with DG penetration maximization.
6. Dynamic programming—this approach is utilized to determine the appropriate size and position of multiple DGs, with the main goal of maximizing utility operator efficiency under various loading situations [33]
7. Nonlinear programming—using optimal load flow, this approach is a mathematical strategy for determining the optimized solution taking nonlinear constraints or objective functions into account [34].
8. Load model—this approach is utilized to determine the size of DGs in distribution systems with fixed and constant and variable power flows, this approach is used to find and size the DGs. In stability studies, load models are quite important [35].
9. Contingency analysis—this approach is employed to assess the influence of DG size and placement on the distribution system following the occurrence of a failure. To compute voltage regulation of the system, the voltage shape of the DG is analyzed prior to and following the occurrence of the failure. The size and location of DGs can be determined dependent on loading conditions and network setup [36].

2.4.2. Analytical approaches

Analytical approaches are a collection of numerous techniques used for assessing the qualitative and quantitative features of network. A detailed review of the analytical approaches based on mathematical expressions discussed in the following:

1. 2/3 rule approach—employed for the distribution systems with equally distributed loads. According to this rule, the installed DG with a 2/third rating of the system is placed at 2/third length of a line [37].
2. Kalman's filter approach—it is utilized with OPF analysis to determine the optimal size of multiple DGs [38]. After using OPF to locate all the DGs in the system, Kalman's filter is utilized to determine their appropriate size.
3. Loss sensitivity factor approach—utilized to determine the proper size and position of all DGs based on load flow analysis and calculate their equivalent current injections. It makes use of matrix algebra [39].
4. Exhaustive load flow approach, it is based on the power factors of the installed DGs. The calculation procedure is carried out two times: first for calculating losses and again for reducing losses [40].
5. Improved analytical (IA) Technique—this approach is utilized to determine the best placement and size for multiple DGs. All the DGs' active and reactive powers, as well as their power factors, are factored into the IA expression [41].
6. Exact loss formula—it is an analytical approach utilized for constructing a formula that incorporates the accurate relationship between the power losses and optimal DGs location and sizing. Nonlinear curves are produced between optimal location and size of DG and the system losses [42].
7. Analytical approach with micro-generation—it is an approach presented in [43]. It is an approach used for optimal sizing, placement, and number of DGs to be installed in the network. It is developed based on a new formulation for the power flow problem, which is noniterative and direct convergence. In addition, this power flow solution is very useful whenever fast and repetitive power flow evaluations are required.

2.4.3. Heuristic approaches

Heuristic approaches are a type of optimization approaches that is used to determine the optimal feasible solution from a group of alternatives. A detailed review of the heuristic approaches is presented in the following:

1. Genetic algorithm (GA)—it is a biology-inspired algorithm designed to find the optimal placement and size of DGs using the genetic code built from genes. Based on several load models, GA is used to find the best position and size of DGs to enhance utility operator profit by determining the optimum placement and size of DGs in the distribution network [44].
2. Particle swarm optimization (PSO)—a method inspired by the social aspects of bird swarm and based on natural phenomena. The approach resembles the genetic algorithm in many ways. The PSO is utilized to determine the proper placement of DGs in a distribution system while minimizing the real and reactive losses [45]. In Ref. [46], the PSO algorithm is used to find the optimal location and size of DGs in a distribution system with different PFs of DGs at different load models.
3. Ant colony optimization (ACO)—a strategy based on the behavior of ants who seek out the shortest way to food.

The ACO method, as proposed in Ref. [47], is utilized to determine the best size and position of DGs with reducing active power losses.

4 Artificial bee colony (ABC)—a strategy based on the behavior of honeybee swarms, which have sophisticated foraging abilities. In Ref. [48], ABC is utilized to determine the best position and size of DGs at different PFs and active power losses.
5 Differential evolution (DE)—an evolutionary method that improves outputs in steps based on defined constraints. It may also be used to optimize non-continuous objective functions. The DE is utilized to determine the appropriate placement and size of installed DGs based on the voltage sensitivity of buses [49].
6 Harmony search (HS)—a musically built heuristic strategy for locating the perfect condition of harmony. The challenge of obtaining the optimal placement of DGs using the loss sensitivity factor technique is further handled using the HS algorithm to find the optimal sizes [50].
7 Tabu search (TS)—a numerical optimization approach that uses user-defined rules or search tables to discover the best potential solution. For uniformly distributed loads, the TS algorithm is used to identify the optimal location and size of DGs under power loss reduction and voltage improvement criteria [51].
8 Big bang big crunch algorithm (BB-BCA)—is an approach based on the big bang and big crunch hypotheses of the cosmos. The objective function creates a random set of solutions in the big bang plane and delivers them to the big crunch plane. BB-BC, as used in [52], optimizes the size and placement of numerous DGs depending on system performance metrics.
9 Hybrid optimization methods—Different optimization techniques (e.g., PSO, GA, DE, ABC, ACO, and so on) can be used to produce the best feasible solutions by combining their merits. A hybrid ACO and ABC to find the optimal position and size of DGs while maximizing network economy, voltage stability and lowering power losses and emission rates of linked energy resources [53]. In Ref. [54], a hybrid TS and GA was used to identify the optimal location and size of DGs, with the main aim on increasing the voltage profile and lowering the power losses of the examined network. A hybrid GA and PSO approach to discover the best position and size for numerous DGs is employed in Ref. [55].

3. Problem Formulation and Power Flow Overview

The main purpose of this study is the optimal integration of distributed generators in the radial distribution networks by finding the optimal placement and sizing to optimize the power losses and improving the voltage profile. The power flow analysis is studied with different methods like Triangular Factorization Method, Newton Rapshon, Gauss, Gauss–Seidel and fast decoupled method etc. [56]. A PSO and GA optimization algorithms are adopted to solve the objective optimization function of OPF subjected to various constraints to reduce loss minimization and to improve the voltage profile.

Power flow studies and load flow are essential for designing, operation, scheduling, exchanging power between networks and control of an existing system and arranging its potential enlargement. Power flow analysis is essential for projection and management of power systems. The power flow analysis helps to analyze the bus voltage, line current, phase angle, active and reactive power flow, and losses in each line.

3.1. 'PQV' based formulation of optimal flow problem

The real power P_i and the reactive power Q_i entering the network at bus-i is given by:

$$P_i - jQ_i = V_i^* \sum_{j=1}^{N} Y_{ij} V_j \angle\theta_{ij} + \delta_j \tag{1}$$

where Y_{ii} are the Y-matrix main diagonal elements called driving point or self-admittance of the buses, and each equals the sum of all the admittances connected to repeated scripts, Y_{ij} is the transfer admittance, and each equals the negative of the sum of all admittances connected directly between the buses identified by the double scripts and it is equal to zero if there is no connection between bus i and bus- j. Sorting and splitting the real and imaginary parts of (1), yields:

$$P_i = \sum_{j=1}^{N} \left|Y_{ij} V_i V_j\right| \cos\left(\theta_{ij} - \delta_i + \delta_j\right) \tag{2}$$

$$Q_i = -\sum_{j=1}^{N} \left|Y_{ij} V_i V_j\right| \cos\left(\theta_{ij} - \delta_i + \delta_j\right) \tag{3}$$

$$P_i = \sum_{j=1}^{N} V_i V_j \left[G_{ij} \cos\left(\delta_i - \delta_j\right) + B_{ij} \sin\left(\delta_i - \delta_j\right)\right] \tag{4}$$

$$Q_i = \sum_{j=1}^{N} V_i V_j \left[G_{ij} \sin\left(\delta_i - \delta_j\right) + B_{ij} \cos\left(\delta_i - \delta_j\right)\right] \tag{5}$$

where G_{ij} and B_{ij} are relevant real and imaginary terms of the transfer admittance Y_{ij} of Y-bus matrix elements of buses-i and j, respectively. The calculation of power flows allows active and reactive loss calculation in different network lines, as well as the total system losses.

3.2. Optimal power flow equations and constraints

OPF is optimized by several equality and inequality constraints involving the various operational conditions and limitations of the power system [57]. The equality constraints are including the active and reactive power balance at each bus while the inequality constraints are including lower and upper constraints of electrical variables and parameters of power system.

To include the active and reactive power of all DGs candidate buses, the power injection can be represented as difference between generation and demand at each bus as,

$$P_i = P_{gi} + \rho_i P_{DGi} - P_{di} \tag{6}$$

$$Q_i = Q_{gi} + \rho_i Q_{DGi} - Q_{di} \tag{7}$$

where P_{gi}, Q_{gi} are generated active and reactive power, respectively at bus-i; P_{di}, Q_{di} are the demand active and reactive power at bus- i, respectively, P_{DGi}, Q_{DGi} are the DG provided active and reactive power and ρ_i is the choice index for DG at bus i with values {0, 1}, which equals one at the existence of DG and zero otherwise. Given the total losses of real and reactive power in the system, the power balance should be included as equality constraints as:

$$P_{GT} - P_{LT} - P_{DT} = 0 \tag{8}$$

$$Q_{GT} - Q_{LT} - Q_{DT} = 0 \tag{9}$$

where GT, DT and LT denote the total generation including DG generations, total load demand and total power losses of the system.

The total active and reactive power loss of the network can be determined by adding the losses of all lines as [58]:

$$P_{LT} = \sum_{i=1}^{N} \sum_{j=1}^{N} \alpha_{ij} \left\{ \left(P_i P_j + Q_i Q_j \right) + \beta_{ij} \left(Q_i P_j - Q_j P_i \right) \right\} \tag{10}$$

$$Q_{LT} = \sum_{i=1}^{N} \sum_{j=1}^{N} \gamma_{ij} \left\{ \left(P_i P_j + Q_i Q_j \right) + \xi_{ij} \left(Q_i P_j - Q_j P_i \right) \right\} \tag{11}$$

where α_{ij}, β_{ij}, γ_{ij} and ξ_{ij} are power loss coefficients given by:

$$\alpha_{ij} = \frac{R_{ij}}{\left| V_i V_j \right|} \cos\left(\delta_i - \delta_j \right) \tag{12}$$

$$\beta_{ij} = \frac{R_{ij}}{\left| V_i V_j \right|} \sin\left(\delta_i - \delta_j \right) \tag{13}$$

$$\gamma_{ij} = \frac{X_{ij}}{\left| V_i V_j \right|} \cos\left(\delta_i - \delta_j \right) \tag{14}$$

$$\xi_{ij} = \frac{X_{ij}}{\left| V_i V_j \right|} \sin\left(\delta_i - \delta_j \right) \tag{15}$$

where R_{ij}, X_{ij} are relevant real and imaginary terms of the transfer admittance Z_{ij} of Z-bus matrix elements of buses-i and j, respectively.

The power loss index is considered by dividing the total active power loss with DG integration given in (10) by the total power loss in base case; without DG; (P_L) as:

$$P_{L\_index} = \frac{P_{LT}}{P_L} \tag{16}$$

The first objective function (Of_1) is given as:

$$Of_1 = \min\left(P_{L\_index} \right)$$

Besides the above power balance equality constraints, the inequality constraints are limits of active and reactive power generated and bus voltage upper and lower limits of generators, voltage of load buses, and phase angle limits [59]. The inequality constraints are stated as follows:

(a) Real Power generation limit:

$$P_{gi}^{min} \le P_{gi} \le P_{gi}^{max} \tag{17}$$

(b) Reactive power generation limit:

$$Q_{gi}^{min} \le Q_{gi} \le Q_{gi}^{max} \tag{18}$$

(c) Voltage limit:

$$|V_i|^{min} \le |V_i| \le |V_i|^{max} \tag{19}$$

(d) Phase angle limit:

$$\delta_i^{min} \le \delta_i \le \delta_i^{max} \tag{20}$$

3.3. Voltage deviation index

Improving the bus voltages profile by minimizing the bus voltage variation from the nominal voltage is one of the most common power quality and safety indices for stability issues. In addition, the improvement of network bus voltages can efficiently decrease the reactive power loss of the network. The voltage deviation at ach bus must be within the lower and upper voltage limits to ensure power quality and voltage stability, which are assumed, within ±6% of nominal voltage of each bus. The voltage deviation index is given as [60]:

$$V_{D\_index} = \sum_{i=1}^{N} \frac{\left| V_{ref} - V_i \right|}{V_{ref}}, i = 1, 2, \ldots, n \tag{21}$$

V_{ref} is the nominal bus voltage, always taken 1.0 p.u., and V_i is the actual bus-i voltage. The second objective function $\left(Of_2 \right)$ is given as:

$$Of_2 = \min\left(V_{D\_index} \right)$$

4. Multi-objective Optimization

Several optimal solutions originating from trade-offs between conflicting objectives are essential in multi-objective optimization (MOO). Following the discovery of a set of such trade-off solutions, the user can employ higher-level qualitative considerations to select between them, a process known as "ideal MOO" [61]. An additional simple technique is to create a composite objective function as the weighted sum of the objectives, with each objective's weight proportionate to the important factor provided to it. The MOO problem is transformed into a single-objective optimization problem using this method of scalarizing an objective vector into a single composite objective function. This procedure is called a "preference-based MOO" or "weighted sum method."

4.1. Weighted-sum multi-objective

By use of the penalty function, a multi optimization problem with multi-objective function is converted to a single optimization problem with a weighted sum. In this paper, the preference-based MOP concept is used to handle the multi-objective problem defined as a single objective one [62]. The MOP problem is defined by combining the power loss and voltage deviation indices given in (16) and (21) using prober weights to formulate a single objective function as follows:

$$f = k_1 (Of_{1)} + k_2 \left(Of_2 \right) \tag{22}$$

where k_1 and k_2 are the weights that designated based on the importance given to each index in the range of (0, 1) subject to $\sum k_i = 1.0$. In this paper, $k1$ and $k2$ are assumed equal to 0.5, since both power loss and voltage deviations are considered have the same impotency.

4.2. Objective functions and constraints The objective function is minimized subject to the operation constraints of power flow balance, active and reactive power generating limits, and voltage limit. The objective function prevents the voltage from violating the limits and minimize power loss of the system. PSO, VCPSO and GA algorithms are used as optimization techniques using the objective function (22), with operational constraints of (17)–(20).

The objective function is to minimize the total system real power loss and voltage deviation given in (22). The optimization problem can be mathematically formulated as follows

$$OF = Minimize\, f(x, u) \tag{23}$$

subjected to

$$g(x, u) = 0 \tag{24}$$

$$h(x, u) \leq 0 \tag{25}$$

where $f(x, u)$ is the objective function to be optimized, $g(x, u)$ is the equality constraints representing nonlinear power flow equations, and $h(x, u)$ is the inequality constraints and u is the system independent decision variables including:

Generating active and reactive power P_{gi} and Q_{gi} at bus i, except slack bus P_{g1}.

Generator bus voltage V_{gi}.

- DG injecting active and reactive power P_{DGi} and Q_{DGi} at bus i.
- DG location (bus number) ρ_j at bus j.

$$u = \left[P_{gi}, Q_{gi}, V_{gi}, P_{DGi}, Q_{DGi}, \rho_j,\right] \qquad \text{for } i = 2, \ldots, N \tag{26}$$

All buses are designated as candidate buses for DG allocation, so there is no limitation in the location of the DGs except the number of DGs. The location should be an integer value; discrete variables; from 2 to 33 (bus number). Also, x is the vector of dependent variables including:

Slack bus generated active power and reactive P_{g1} and Q_{g1}.

Magnitude of load (PQ) bus voltage and phase angle V_{Li} and $+\delta_i$.

$$x = \left[P_{g1}, Q_{gi}, V_{Li}\right] \qquad \text{for } i = 1, \ldots, N \tag{27}$$

To maintain power balance, the difference between the sum of power generated by each generator and DGs must equal the total power losses. As a result, the power balance (8) and (9) should be included as equality constraints $g(x, u)$ represented by (24) as follows:

$$P_{\mathrm{LT}} = \left(\sum\nolimits_{i=1}^{N} P_{gi} + \sum\nolimits_{j=1}^{N_{DG}} P_{DGj}\right) - \sum\nolimits_{i=1}^{N} P_{di} \tag{28}$$

$$Q_{\mathrm{LT}} = \left(\sum\nolimits_{i=1}^{N} Q_{gi} + \sum\nolimits_{j=1}^{N_{DG}} Q_{DGj}\right) - \sum\nolimits_{i=1}^{N} Q_{di} \tag{29}$$

where P_{gi}, Q_{gi} are the active and reactive power generated at bus; P_{DGi}, Q_{DGi} are the active and reactive power injected from the jth DG unit; P_{di}, Q_{di} are the active and reactive power load connected at bus i and N_{DG} is the total number of DG units installed in the distribution network. In the above expressions, losses are a function of the net active (P_{DGj}) and net reactive (Q_{DGj}) power injected on each bus of the network.

The final equality constraint is the total DGs installing capacity and the total numbers of DGs to be installed. These constraints can be represented as:

$$\sum\nolimits_{j=1}^{N_{DG}} P_{DGj} = C \tag{30}$$

$$\sum\nolimits_{j=1}^{N_{DG}} \rho_j = N_{DG} \tag{31}$$

where C is the total DG capacity.

The inequality constraints $h(x, u)$ described by (25), are the power system operating limits given by (17)–(20). Finally, the problem becomes a constrained mixed integer nonlinear multivariable optimization with four equality constraints.

5. Particle Swarm Optimization (PSO)

In classical PSO, random particles are initially created in the search space and the best solution among these particles is selected, forcing position and movement of each particle at the present state to be remembered. The particles positions at the next step will be renewed from the previous position and movement values, given that the whole swarm is taking an action to improve the fitness value and next improvement can be achieved. The best fitness (the smallest solution) is selected and guiding the reminder particles to be pushed to this best solution. The updated particle velocity is obtained by the deviation between the particle position and best position among all particles (*gbest*), plus the incremental between the current position of this particle and its best position ($Pbest_i$). Similarly, the updated position is obtained by summing the movement of the particle to its current position. The updated particle position and velocity are determined as:

$$V_i^{k+1} = wV_i^k + c_1 rand\left(pbest_i - S_i^k\right) + c_2 rand\left(gbest - s_i^k\right) \tag{32}$$

$$S_i^{k+1} = S_i^{\mathrm{k}} + V_i^{k+1} \tag{33}$$

where S_i and V_i are the particle position and velocity, respectively. The control parameters of the PSO are inertia weight (ω), acceleration coefficients (c_1, c_2), random constants (r_1, r_2) between 0 and 1.

The PSO algorithm consists of just three main steps: (1) During each iteration, each solution is evaluated by an objective function to determine its fitness value, (2) Update individual ($Pbest_i$) and global bests (*gbest*), and (3) Update velocity (V_i) and position (S_i) of each particle. These steps are repeated until some ending criteria is encountered as the number of specified iterations or an error criterion be reached. Table 1 lists the parameters and constants of the PSO proposed in this work.

A major disadvantage of the classic PSO in solving Optimization problems is that it can stuck in a local maximum, resulting in a loss of exploration capabilities. The PSO parameters ω, c_1 and c_2, affect the PSO performance significantly, where inappropriate parameters may result in least premature convergence or even divergence of the PSO solution.

Table 1. PSO and GA control parameters

	Parameter	Symbol	Value
PSO	Number of particles		10
	Number of iterations		50
	Acceleration constants	c_1	0.7
		c_2	0.7
	Inertia weight	ω	0.9
GA	Population size		300
	Number of generations		50
	Crossover rate		95%
	Elitism rate		5%
	Mutation rate		10%

5.1. Variable coefficients or dynamic PSO Numerous attempts have been developed to enhance the characteristic of the classical PSO technique to discover the best set of control parameters. A variety of rules can be used to find optimal control parameters instead of using fixed parameters. Variable coefficients or dynamic particle swarm optimization (VCPSO) is presented with the linear decreasing control parameters as follows:

$$w^k = w_{max} - \frac{k}{k_{max}} \cdot (w_{max} - w_{min}) \tag{34}$$

$$c_1^k = c_{1max} - \frac{k}{k_{max}} \cdot (c_{1max} - c_{1min}) \tag{35}$$

$$c_2^k = c_2min + \frac{k}{k_{max}} \cdot (c_{2max} - c_{2min}) \tag{36}$$

where inertia weight in the range from $w_{max} = 1.0$ to $w_{min} = 0$, the acceleration coefficients in the range $c_{1min} = c_{2min} = 1.0$ and $c_{1max} = c_{2max} = 2.0$, and k_{max} is the maximum number of iterations.

6. Results and Discussions

To confirm the validation and the effectiveness of the proposed analysis and the presented optimization methods, the study is tested on the IEEE 33-bus standard distribution network at different case studies: (1) base case: the system is without distributed generators, (2) case 1: the systems is with one optimal DG unit installed at the optimal location in the system, (3) case 2: two DG units integrated at the their optimal locations, (4) case 3: three DG units integrated at their optimal locations. All case studies are implemented in MATLAB 2019b to optimize the multi-objective function, and simulations are carried out on a PC having Intel® Core™ i7-6700 CPU @ 3.4GHz RAM. Detailed results and discussions are presented in the following:

The tested IEEE 33-bus distribution network without DG integration is treated as the base case for evaluation and power flow analysis is implemented using Newton–Raphson method. Figure 5 shows the comparison of total active and reactive power losses for the three studied cases compared to the base case without installing DGs. The active and reactive power losses for the base case are fund to be 211.2 kW and 140.5 kVAR, respectively, with the lowest bus voltage is 0.9034 at bus # 18. In case 1, when one DG integration the optimal DG size is found to be 2.5914 MW and the optimal placement is at bus # 6. The total active and reactive power loss at this case is 111.1 kW and 73.91 kVAR, respectively.

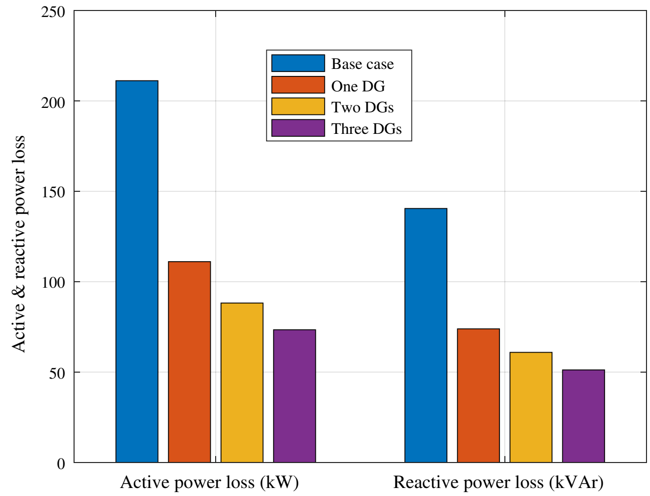

Fig. 5. Comparison of active and reactive power loss

Table 2. Power loss and voltage improvement comparison

Method	VCPSO	PSO	GA
Active power loss (kW)	111.1	111.2	111.2
Reactive power loss (kVAr)	73.56	73.59	73.87
Lowest voltage and location	0.948/18	0.942/18	0.944/18
Optimal DG size and location	2.5910/6	2.5914/6	2.5923/6
Computation time (s)	29	78.3	492

In case 2, with two DGs integration, the DG units of size 0.8667 and 1.3232 kW at buses 13 and 30, respectively with the active and reactive power losses of 88.2 kW and 60.9 kVAr, respectively. In case 3, with three DG units, the sizes of 0.7095, 1.2604, and 1.1184 kW at buses # 14, 24 and 30, respectively with the total active and reactive power losses of 73.4 kW and 51.2 kVAR. The obtained results are listed and compared in Table 2. From Fig. 5, it can be noted that installing multiple DGs in the distribution systems provides better improvements in the active and reactive power losses than installing one DG. It should also be noted that the reactive power has improved even though it was not present in the objective of (22), this because of the improvement in the bus voltages.

Figure 6 shows the comparison of the convergence characteristics of the three algorithms. The performance illustrates that the presented VCPSO algorithm discoveries a good zone of the search spaces at the first iterations and rapidly settles to the optimal solution compared to the other classical PSO and GA techniques. It takes only 10 iterations and compared to 27 and 43 iterations, respectively, for the other two techniques. The simulation times are 29, 78.3 and 492 s for the three techniques carried out on a PC with Intel® Core™ i7-6700 CPU @ 3.4 GHz RAM. Table 3 shows the performance comparison and the computation time of the three methods.

The optimal size of one DG located at each bus is calculated and it found to be in the range of 4.1462–0.3431 MW at buses at bus # 2 and 22, respectively. Figures 7 and 8 illustrate the optimal size of the DG that should be integrated at each bus and its corresponding variations in the total active power loss. It is obvious to note that the optimal size of the DG does not follow a

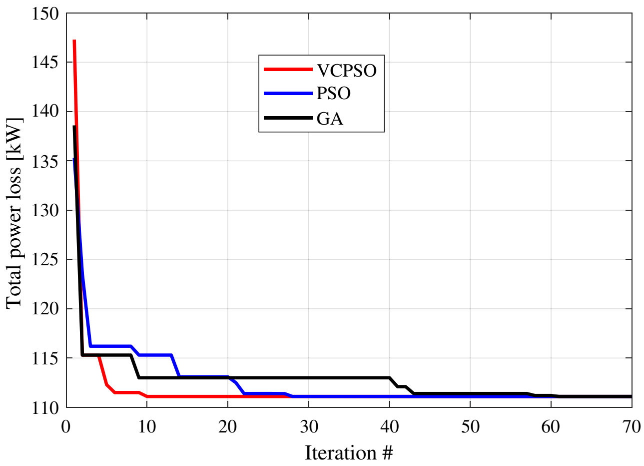

Fig. 6. Convergence characteristics of presented algorithms

specific rule, it depends only on the bus location and the integration of the optimal size of DG at any bus results in the decrease in the total active power loss in contrast to other studies which stated that inappropriate location of optimal size of DG may lead to increased active power losses. However, the total active power loss reduction varies with the bus integration of DG and the optimal size of 2.5914 MW at bus # 6 leads to the minimum active power loss of 111.1 kW as compared to 211.2 kW in the base case with an improvement of 47.4%. The least improvement in the total active power loss is happened when the optimal DG sizes are located buses # 20, 21 and 22 with a power loss of 209 kW, which almost equal to that of the base case. The active power loss variations at each line with the optimal DG size integrated for different scenarios as compared to the base case are depicted in Fig. 9. The total losses at each line have considerably decreased as can be noticed from Fig. 9, especially for lines one to eight.

The comparison of per unit values of bus voltage variations with optimal DG size and placement for different cases as compared to the base case are depicted in Fig. 10, while Fig. 11 shows the bus voltage variations for one optimal DG placed at optimal location. All bus voltages are improved with optimal DG integration compared to the base case with a considerable improvement up to 8.6% at some buses near the generation and less improvements at the far end buses. Table 4 shows the far end bus voltages improvements with optimal DG integration for one DG placement. Similar to the improvements in the total active power loss shown in Fig. 10, integrating optimal DG at any bus results in improving the voltage variations at all buses compared to the base case but with different improvement ratios. However, optimal sizing and placement of DG does not necessarily guarantee the optimal

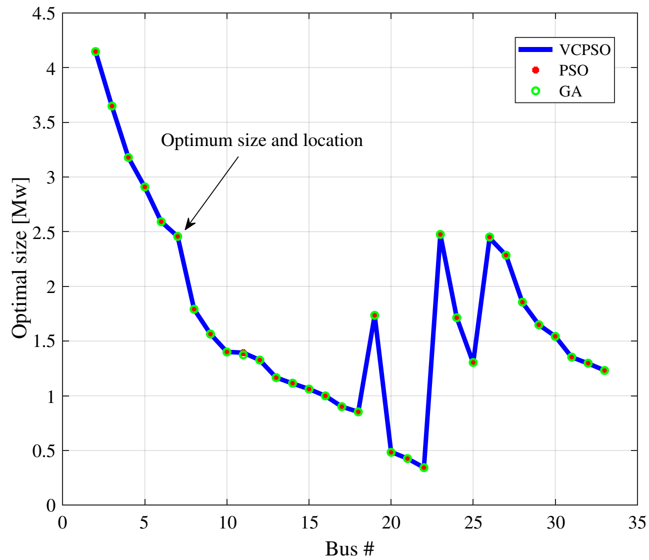

Fig. 7. Different optimal DG sizes at different placements

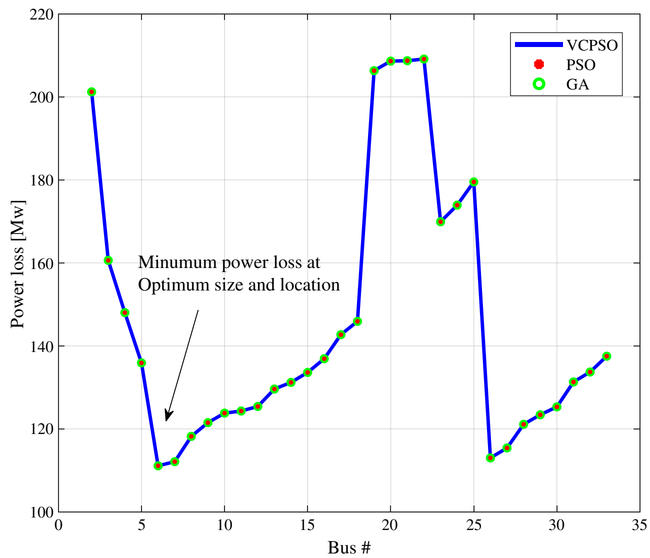

Fig. 8. Active power loss with one optimal DG at different placement

improvement in the bus voltage variations. Therefore, voltage variation index should be included in the objective function, second part of (24), to guarantee optimal voltage improvements.

Table 3. Performance comparison of VSPSO, PSO and GA

	Base case	One DG	Case 2: Two DGs	Case 3: Three DGs
Active power loss (kW)	211.2	111.1	88.2	73.4
Power loss reduction	-	47.40%	58.24%	65.25%
Reactive power loss (kVAr)	140.5	73.91	60.90	51.20
Reactive power loss reduction	-	47.40%	56.66%	63.56%
Lowest voltage and location	0.904/18	0.948/18	0.9716/18	0.9679/18
Bus voltage improvement	-	4.8%	7.48%	7.28%
Optimal DG sizes (MW) & location	-	2.5910/6	0.8667/13 1.3232/30	0.7095/14 1.2604/24 1.1180/30

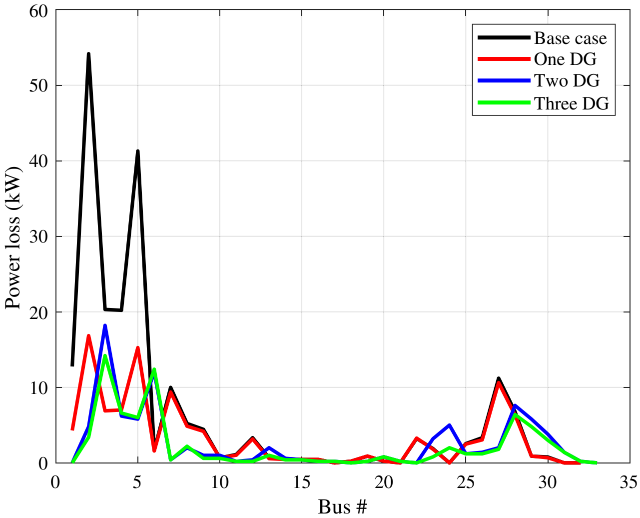

Fig. 9. Total active power loss variations with different scenarios

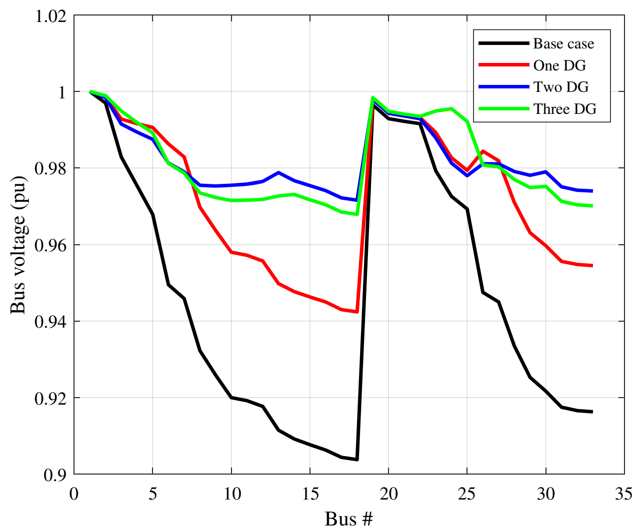

Fig. 10. Variation of bus voltages with different scenarios

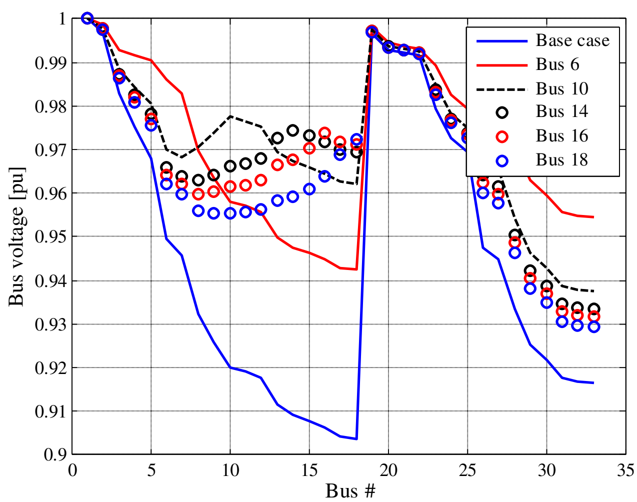

Fig. 11. Variation of bus voltages without and with optimal one DG integration

Table 4. Far end bus voltage improvement with optimal DG integration

	Voltage (pu)		
Far end Bus #	Base case	Optimal DG	Reduction
18	0.9028	0.939	3.88%
22	0.9926	0.9939	0.13%
25	0.9692	0.979	0.997%
33	0.917	0.9955	8.6%

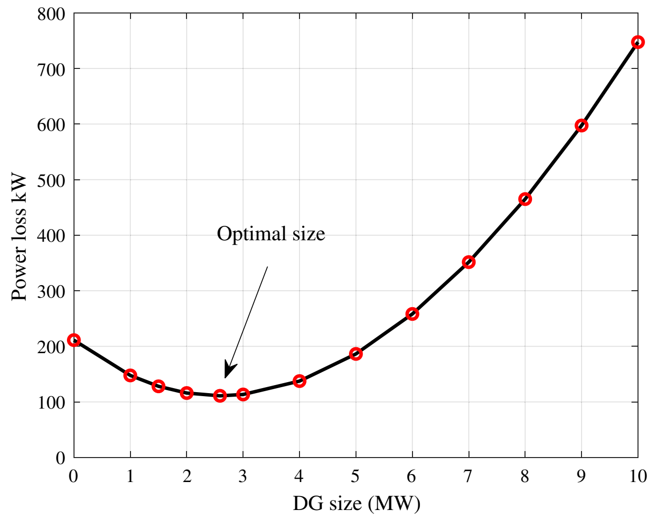

Fig. 12. Power loss characteristic with DG size variations

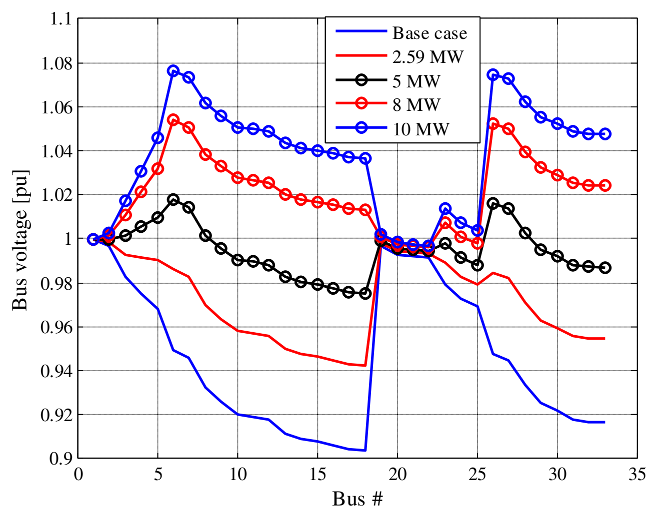

Fig. 13. Variation of bus voltages with non-optimal DG size

Table 5. Min, max, mean and std values of the compared algorithms

	GA	PSO	VCPSO
Min	111.2000	111.2000	**111.100**
Max	113.0549	112.9780	**112.2676**
Mean	111.6770	111.7997	**111.2751**
Std	1.4394	1.3767	**1.16270**
SR	0.86	0.94	**1.0**

Note: The bold indicates the obtained results from the proposed approach.

Table 6. Comparison of optimal DG locations and sizes in the IEEE 33-bus radial distribution system

Case	Ref.		Opt. bus	Size(s), (MW)	Total size (MW)	Power loss		Loss reduction %		Min voltage (p.u.)	
						Active	Reactive	Active	Reactive	Value	Bus #
1 DG	**Proposed**		**6**	**2.591**	**2.591**	**111.1**	**73.91**	**47.4**	**45.77**	**0.948**	**18**
	Haider [61]		6	3.134	3.134	110.2	79.43	45.8	41.2	0.948	18
	Hung [63]	LSF	18	0.743	0.743	146.82	—	30.48	—	—	—
		IA	6	2.601	2.601	111.1	—	—	47.39	—	—
		ELF	6	2.601	2.601	111.1	—	—	47.39	—	—
	Kumar [64]		6	3.001	3.001	64.79	5.50	—	—	0.965	18
	Prakash [65]		6	2.589	2.589	110.99	—	47.39	—	—	—
2 DGs	**Proposed**		**13**	**0.8667**	**2.1899**	**88.2**	**60.90**	**58.24**	**56.66**	**0.9716**	**18**
			30	**1.3232**							
	Haider [61]		6	3.1334	3.499	105.7	74.81	47.97	44.65	0.9573	32
			16	0.3651							
	Hung [63]	LSF	18	0.720	1.620	100.69	—	52.32	—	—	—
			33	0.900							
		IA	6	1.800	2.520	91.63	—	56.61	—	—	—
			14	0.720							
		ELF	12	1.020	2.040	87.63	—	58.51	—	—	—
			30	1.020							
	Kumar [64]		6	2.005	2.967	43.279	—	—	—	0.965	18
			31	0.962							
	Prakash [65]		6	1.899	2.5486	91.3	—	56.73	—	—	—
			14	0.6499							
3 DGs	**Proposed**		**14**	**0.7095**	**3.0883**	**73.4**	**51.20**	**65.25**	**63.56**	**0.9396**	**33**
			24	**1.2604**							
			30	**1.1184**							
	Haider [61]		6	2.1642	3.2679	82.77	58.39	59.26	56.80	0.9461	33
			16	0.3651							
			25	0.7386							
	Hung [63]	LSF	18	0.720	2.430	85.07	—	59.72	—	—	—
			33	0.810							
			25	0.900							
		IA	6	0.900	2.520	81.05	—	61.62	—	—	—
			12	0.900							
			31	0.720							
		LSF	13	0.900	2.700	74.27	—	64.83	—	—	—
			30	0.900							
			24	0.900							
	Kumar [64]		6	1.789	3.597	30.29	25.343	—	—	0.9649	18
			31	0.962							
			25	0.848							
	Prakash [65]		14	0.691	2.9544	74.09	—	64.88	—	—	—
			24	0.9861							
			29	1.2773							

Note: —: not available.

The effect of non-optimal DG size on the total power loss and bus voltages are demonstrated in Figs 12 and 13, respectively. As the size of the integrating DG increases, the total active power loss decreases to the optimal minimum value, and then any increase in the DG size leads to an increase in the total active power loss. Figure 12 shows the variations of the total active power loss variation as the DG size varies between 0 MW (base case) to 10 MW at bus 6. As the size of the DG is increased to the optimal value, the power loss is minimized. The minimum total active power loss is at the integration of DG size of 2.59 MW. Further increase in the DG size above the optimal value degrades the active power loss profile. The configuration of distribution networks is as the power flow should be from the network substation to the consumer where conductor sizes decrease regularly. When the DG is installed in the distribution system, it is desired that power is utilized within this distribution network and thus power loss is improved. Any DG size greater than the optimum size will result in reverse flow of power towards distribution substation. Therefore, excessive power flow through little-sized conductors towards the transmission system leads to an increase of the power loss in the system.

The bus voltage variations with non-optimal DG size at bus 6 are shown in Fig. 13. The voltage profile is improved with all sizes of DG to certain limit at each size. It can be noted that, the size of the

DG hardly affects the voltage profile stability index at particular buses and may lead to over voltages above the nominal values as depicted in Fig. 13. From Figs 12 and 13, it can be deduced that the total active power loss in the distribution system can be reduced significantly, and bus voltage profile can be improved by identifying the optimal placement and size of DGs.

The optimization problem is executed in 100 independent running and the results attained by the three algorithms are compared. Table 5 displays the active power losses obtained, as well as the minimum (Min), maximum (Max), Mean and standard deviation (Std) values and success rate (SR). Success rate represents the proportion of successful runs in terms of the total runs (a successful run is where the obtained objective function value is within 2% of the known optimal value). As it can be seen from Table 8, superior solutions have gained from results that made with VCPSO than compared other algorithms in Min, Max and Mean values. It is also clear that the Std value, which depicts the dispersion of the solutions around the computed mean values, outperforms the PSO, which came in second after the VCPSO.

To evaluate the computational performance of the presented algorithms, comprehensive comparisons have been performed with various methods found in Refs [63–65,87]. The comparison is carried out with respect to The DG locations, sizes, active and reactive power losses, value and location of minimum bus voltage. Table 9 presents the comparison of various techniques, optimization methods and the objective function used in literature for optimal sizes and placement of DG systems for IEEE 33 bus radial distribution network.

Detailed comparisons of optimization outcomes achieved by applying the presented algorithms as compared to other methods are given in Table 6. From this comparison, it can be observed that the presented algorithms can provide proper DG locations and accurate DG sizes in cases of single and multiple DGs compared to other methods found in literature.

From obtained results, installing multiple DG achieves better results than installing one DG. Also, the presented algorithms proved their effectiveness to obtain the best sizes and locations of DG that lead to better reduction in system losses than other efficient algorithms.

7. Conclusion

Multi-objective optimizations using three optimization techniques of PSO, VCPSO and GA algorithms are applied to find the optimal size and placement of multiple DGs integrated into electrical power network. The paper conducted a detailed review of DG definition, classifications, technologies, optimization objectives and impacts into power systems. Then, the multi-objective optimal sizing and placement of multiple DGs have been investigated to mitigate the total active power loss and improve bus voltage profile of the distributed networks. The presented analysis and optimization techniques are assessed on the standard IEEE-33 bus distribution network and the optimization were carried out using MATLAB. The obtained outcomes are evaluated and compared with other methods. The comparison proved that the presented VCPSO algorithm offered an improved solution for the optimal placement and size of DGs in terms of the accuracy of the global optimality with best convergence and lowest computation time. Four case studies have been studied with different number of DGs. In case 1, base case, the total active and reactive power losses were 211.2 kW and 140.5 KVAR, respectively and the minimum voltage was 0.904 pu at bus #18. After integrating one optimal DG of 2.59 MW at bus #6, the active and reactive power losses decreased to 111.2 kW and 73.91 kVAR, respectively, and the minimum bus voltage was improved to 0.948 pu at bus #18. After integrating two DGs and three DGs, the losses are decreased to 88.2 kW, 60.9 kVAR and 73.4 kW, 51.2 kVAR, respectively. The presented results proved that the integration of optimal size and location of DGs are efficient in terms of decreasing the total active and reactive power loss and voltage profile, while improper sizing leads to negative impacts.

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