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Optimal Placement of Distributed Generation and Capacitors in Radial Distribution Networks Using Hybrid Evolution Programming Algorithm

Chege S.N., Murage D.K. and Kihato P.K.

Department of Electrical and Electronics Engineering, Jomo Kenyatta University Agriculture and Technology, Nairobi, Kenya
snchege@jkuat.ac.ke

ABSTRACT
Distribution systems form a critical part of the power system by linking the consumer to the transmission system. They are extensive and complex and require adequate planning. One of the main challenges in distribution networks is voltage instability. Voltage instability can be mitigated by distributed generation and capacitor placement in distribution networks. The effectiveness of these components is greatly dependent on how optimal they are placed and sized within the distribution network. Due to complexity of distribution networks, planning becomes a complex task, and therefore new techniques require to be developed to assist network planners optimally place capacitors and distributed generation in distribution networks.
In this paper, a novel way of optimally placing and sizing Distributed Generation and capacitor is applied. The method uses Voltage Stability Index to find the optimal location of Distributed Generation and Capacitors. Hybrid Evolutionary programming algorithm is employed to determine the optimal sizes of Distributed Generation and Capacitors to be placed at the identified locations. The aim is to enhance the voltage stability of the radial distribution network. This method is tested on the IEEE 33-bus radial distribution network. Simulation is carried out in MATLAB.

Key words: Capacitor Placement, Distributed Generation, Hybrid Evolution Programming, Voltage Stability Index

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INTRODUCTION

A power system network has four important segments namely generation, transmission, distribution and utilization. These segments are required to be planned and operated securely in order to maintain a given frequency and voltage level. Traditionally, voltage in distribution systems is controlled and kept within a specified range using various devices such as static VAR compensators and on-load tap changers. The operation of these devices is usually coordinated to ensure proper operation [1].
In the last few years, the demand for electric power has greatly increased due to economic growth and increasing population especially in developing countries. This has caused distribution systems be operated close to their maximum limits of voltage stability and power carrying capacity. In addition, distribution systems have changed from passive networks to active networks due to increased proliferation of distributed generation [2]. Increased proliferation of distributed generation has resulted in a number of adverse effects. These effects include voltage variation, degraded protection, altered transient stability, bidirectional power flows and increased fault level. Voltage variation has been addressed as the most dominant impact of distributed generation [3].
Voltage stability is a requirement for the secure operation of distribution systems. Proper planning of Distributed Generation (DG) and their control strategies determine the voltage stability situation of distribution system [4-5]. The planning aspect involves proper location and sizing of the DGs together with other reactive power sources in the distribution network. Control aspect involves the coordinated operation of these DGs together with conventional voltage and reactive power devices [6].
With the advent of DGs, it has become critical to incorporate them in distribution system planning. The distributed generation placement problem has been a key area of research in the recent past. Different researchers have addressed the

DG placement problem in different ways. The objective functions used by researchers in DG planning include power loss minimization, reliability enhancement, minimization of operational and investment cost and voltage stability enhancement [7]. The objective function used in this research is maximizing voltage stability.

Many methods have been employed by researchers in DG placement problems. These methods include analytical methods, numerical methods and heuristic methods. Heuristic methods have been found to work well for large and complex optimization problems such as DG and capacitor placement problem [8]. Heuristic methods that have been used in DG and capacitor placement planning include particle swarm optimization [9-10], bacteria foraging algorithm [11], differential evolution algorithm [12] and ant colony algorithm [13]. These individual search heuristics, however, suffer poor local optimization when the size of the search space is large. It is therefore common practice to use hybrid search heuristics to solve optimization problems to alleviate this problem. Hybrid search heuristic methods incorporate more than one search technique and draw advantages of the individual method and therefore resulting in better search results. This research employs a hybrid algorithm which integrates Evolution Programming, Simulated Annealing and Tabu Search to find optimal sizes of capacitors and distributed generation placed at optimal locations for voltage stability enhancement.

Voltage Stability

Voltage stability is the ability of power system to sustain acceptable voltage levels under normal operating conditions and after occurrence a disturbance [14]. Voltage instability is caused by failure of power sources to produce enough reactive power or by failure of power transmission line to transmit demanded reactive power. Reactive power is supplied to a power system by generators or reactive power compensators such as capacitors. Instances that cause voltage instability include increment in load, power system faults and exceeding the reactive power limits of generators [15]. Voltage instability is mitigated by voltage support using distributed generation and capacitors, use of Flexible Alternating Current Transmission (FACTs) devices and load shedding.

Voltage stability is usually represented by active Power-Voltage (P-V) curves, reactive Power-Voltage Q-V curves and stability indices. In P-V curve method, real power at a bus is gradually increased by keeping power factor constant. Repeated power flow studies are done until the Point of Voltage collapse (PoVC) is obtained. PoVC is the nose of the P-V curve. An increase in load beyond the PoVC will lead to rapid voltage drop of the power system and consequently voltage collapse or network collapse. Voltage collapse usually occurs in heavily loaded systems that do not have sufficient local reactive power sources and hence fail to provide secure voltage profile for the system [16].

Q-V curve method of voltage stability analysis shows variation of receiving end voltage with variation in load reactive power for different real power loads. When using the Q-V curve method, the sensitivity of voltage to changes in reactive power at a given bus is given by the slope of the Q-V curve. If the V-Q slope of the i^{th} bus is positive, the system is voltage stable and if negative the system is voltage unstable. Other methods used for steady state voltage stability analysis are modal analysis and sensitivity analysis. These methods use the Power Flow Jacobian that is obtained by solving a set of equations linearized about a given operating point. The Jacobian is evaluated for singularity to determine the maximum loadability of the power system. The main disadvantages of these techniques is that they require considerable computation efforts and are time consuming especially for a large network [17].

Recently, researchers have developed indices for voltage stability analysis in power systems and particularly for analysis in distribution systems. Distribution networks are large and complex and therefore require simple tools for stability analysis that do not require large computational effort. Many indices have been developed by researchers studying voltage stability of power systems as a measure of how far or near a system is from voltage instability or voltage collapse. In [15], a comprehensive review of voltage stability indices has been done. The authors have classified voltage stability indices into three categories namely bus, line and overall stability indices. Line voltage stability indices include Fast voltage stability index (FVSI), Line Stability Index (Lmn), New Voltage Stability Index(NVSI), Line Stability Factor (LQP), Line Stability Index (Lp), Novel line stability index (NLSI), voltage collapse proximity index (VCPI), Voltage reactive power index (VQI_{Line}), Powertransfer stability index (PTSI), Voltage stability index(VSI_L), Voltage Stability Load Index (VSLI) and Line Collapse Proximity Index (LCPI).

Bus voltage stability indices determine stability of system buses and they include Voltage collapse prediction index ($VCPI_{bus}$), L-index, S difference criterion (SDC), Voltage stability index (VSI_{bus}), Impedance matching Stability Index (ISI), Z_L/Z_S ratio, and Simplified Voltage Stability Index (SVSI).

Overall voltage stability indices are not related to buses or lines. They are used to determine the system voltage collapse point. They include load margin, system determinant (SD), second order index, voltage instability proximity index (VIPI), center manifold based index (CMBI), energy functions (EF), reactive power margins (RPM), singular values and eigenvalues.

The Voltage Stability Index (VSI) presented in [18] has been used in this work as the objective function. The index is simple and suitable for voltage stability determination in radial distribution networks. The VSI is formulated as shown equation (1).

$$VSI_i = V_s^4 - 4V_s^2\left(R_i P_{Li} + X_i Q_{Li}\right) - 4\left(X_i P_{Li} - R_i Q_{Li}\right)^2 \quad (1)$$

where,

VSI_i is Voltage Stability Index at Bus i

V_s is distribution substation voltage which is 1 p.u

R_i is resistance between source bus and bus i

X_i is reactance between source bus and bus i

P_{Li} is the active power flow through bus i

Q_{Li} is the reactive power flow through bus i

DISTRIBUTED GENERATION TECHNOLOGIES

Distributed generation can be defined as an electric power source connected directly to the distribution network or on the customer side of the meter [19]. There are many classifications of DGs that vary from type and technologies used. El-Khattam et al [20] has given a comprehensive classification of DG technology. They classified DGs into two broad categories namely traditional generators (combustion engines) and non-traditional generators. Traditional generators include microturbines such as natural gas turbines. Non-traditional generators include electrochemical devices (fuel cells), storage devices (batteries) and renewable devices such as photovoltaics (PV) and wind turbines.

DGs vary in size and their output characteristic is to a large extent determined by the primary energy characteristics. Based on their output characteristics, DGs are either dispatchable or non-dispatchable. Dispatchable DGs can be controlled by the operator to ensure the desired voltage and power output is maintained at the DG bus. However, nondispatchable DGs are difficult to control due to intermittent nature of their output caused by the unpredictability of the primary energy source.

In addition to the above classification, DGs are also classified as Type 1, Type 2, Type 3 and Type 4. Type 1 DGs only deliver active power and include photovoltaics, fuel cells and microturbines. Type 2 DGs deliver both active and reactive power. These DGs are based on synchronous machines. Type 3 DGs deliver only reactive power. They include synchronous compensators such as gas turbines. Type 4 DGs deliver active power while consuming reactive power. Induction Generators used in wind farms are in this category.

Voltage stability of distribution systems with DGs mainly depends on control strategies, capacity and location of the DGs. It is therefore important to know the mode of operation of the DGs during the planning stage so that the effect of their operation on voltage stability is known. DGs are normally operated in power factor control mode where power factor is kept constant [2]. In this mode, the reactive power follows the real power variation. This mode of operation can therefore allow the simultaneous placement of DGs, both dispatchable and non-dispatchable, and capacitors on the same bus with appropriate coordinated control of DG active power and reactive power output, and capacitor reactive power.

Optimization Methods

Power systems optimization is an important area in Power Systems Engineering because it has contributed to savings in terms of fuel cost, improved operational reliability and system security. Power systems have become large and complex and there has been a need to develop optimization techniques that will accommodate the large number of constraints in solving power systems optimization problems. This section addresses the various optimization techniques that have been applied in power systems optimization and in particular, in DG and capacitor placement.

Analytical Methods

These are classical optimization methods which use the classical theories of mathematics such as calculus, algebra and matrices to model physical systems and derive optimal values of system variables. Naresh Acharya et al [21] used an analytical method based on exact loss formula to calculate the optimal size of DG and to identify the optimum location for DG placement with the objective of minimizing total power loss in distribution systems. The analytical approach by these researchers was based on placing a DG in one bus at a time and calculating the network loss for each case until when the minimum loss is obtained. Their method therefore cannot be used to place more than one DGs in different locations at the same time. Jain et al [22] used an analytical method based on two port z-bus parameters to site and size DG for voltage stability enhancement. The authors of this work applied this analytical technique to site one DG in a 69-bus radial distribution network. The efficiency of their method has not been demonstrated in siting more than one DG in the network simultaneously. In [23] an analytical technique based on loss sensitivity has been applied. The method uses the bus-injection to branch-current (*BIBC*) and branch-current to bus-voltage (*BCBV*) matrices to simplify the solution process. This method though is only applied for placing only one DG in the distribution network. From this analysis of literature, analytical methods have been observed not to be effective when dealing with multiple DG placement. They are however effective for single DG placement.

Numerical methods

Numerical methods involve computing numerical data in problems to produce a sequence approximation of data iteratively until obtaining the best solution. Numerical optimization methods include linear programming, ordinal optimization, non-linear programming, dynamic programming, and quadratic programming among others. Linear programming method has been used in [24] to solve the DG allocation problem where the objective function is increasing the generation capacity while ensuring that technical constraints are not breached. Dynamic programming has been used to solve the DG allocation optimization problem in [25] to enhance loss reduction and system reliability. Dynamic Programming decomposes the main problem into a series of single stage decision problems and optimization is done at each stage. Dynamic programming does not guarantee an optimal solution because only a few of the potential solutions are saved during the search process. Mixed Integer Non-Linear Programming (MINLP) has been applied in [26] to solve the DG placement problem with the objective of minimizing the system annual losses. The researchers use a probabilistic based planning approach to determine the optimal fuel mix of different types of DG units considering the uncertainties of renewable DG resources. Numerical methods however are not accurate when solving ill-conditioned equations. This is because of round off errors during the solution process which introduce small changes into the coefficient matrix which in turn introduces large errors to the final solution[27].

Heuristic Methods

Heuristic methods are computed-oriented approaches that use artificial intelligence to search for optimal solutions of an optimization problem. Artificial intelligence methods have simple mathematical structure and simulate natural phenomena such as behaviour of animals. Search heuristics are particularly applicable when objective functions are highly nonlinear and when the number of variables and constraints is large. In addition, search heuristics reduce development time and are robust since they are insensitive to missing data [28]. Researchers have applied heuristic methods in solving the DG and Capacitor optimization problem. Kalman Filtering method has been used in [29] to solve the optimal placement problem of DGs for loss reduction. Kalman filter algorithm has smoothing properties and the ability to reject noise. This algorithm has been used to place multiple DGs which effectively lead to system loss reduction. Since only a small sample of network data is used in Kalman Filter Algorithm, the authors concluded that computational effort was reduced while at the same time reaching optimal solutions.

Particle swarm optimization algorithm has been used in [9]to solve the DG placement problem. Particle swarm optimization was also used in [10] for multi DG problem for enhancing voltage stability. Imran et al. [11] used the Bacteria foraging optimization algorithm to find the optimal size of DGs and capacitors for power loss minimization. Mohapatra et al [12]applied Differential Evolution algorithm for optimal placement of distributed generation and capacitors with the objective of minimizing system losses. In [13], Ant Colony Algorithm has been used to solve capacitor and DG placement problem for loss minimization and improvement of voltage problem in distribution systems. From analysis of literature it is clear that heuristic methods have gained popularity in DG and capacitor placement optimization problem.

Daud et al. [30] have provided a comprehensive review of methods of optimization in DG planning. They reviewed numerical, analytical and heuristic methods and gave a comparison as shown in Table- 1.

Table- 1 A comparison of optimization methods

Method	**Heuristic**	**Numerical**	**Analytical**
Advantages	• Simple, flexible and suitable for solving problems with large search space • Does not require conversion of the power system model into an optimization programming model • can search for a near optimal solution	• Accurate optimal solution	• No convergence problem • Non-iterative • Simple
Disadvantages	• some of the algorithms get trapped in local optima hence resulting in sub-optimal solutions • slow convergence	• Requires conversion of power system equations to an optimization model, a process that is difficult to manage	• Difficult to apply when dealing with large and complex optimization problems such as DG placement in distribution networks • Does not guarantee an accurate solution

From this comparison, it can be seen that heuristic methods are the most suitable when dealing with large and complex optimization problems such as DG and Capacitor placement. Georgilakis et al. [7] also provide a comprehensive review of methods used in DG placement. The authors noted that heuristic methods are most efficient and provide robust and near optimal solutions for large optimization problems. They also suggested the need for improving parameters of heuristic algorithms so as to improve efficiency and quality of solutions from these algorithms. Hybridizing heuristic methods is particularly useful in eradicating the problem of getting trapped in local optima hence improving the performance of individual heuristic method. This work therefore uses a hybrid technique that incorporates Evolution

Programming, Simulated Annealing and Tabu Search in the DG and capacitor placement problem with the objective of enhancing voltage stability in radial distribution networks.

Methodology

The placement problem is formulated based on the Voltage Stability Index presented [18]. This index varies from 0 to 1, with zero representing voltage collapse point and 1 representing the most stable bus. A load flow is done using the Forward-backward sweep load flow method. Voltage stability indices at all buses are determined.

These stability indices are ranked from the smallest to the largest. The maximum number of DGs and Capacitor locations is determined by dividing the maximum DG penetration by the maximum DG size allowable. This number is used to determine the number of buses corresponding to the lowest ranked indices which are taken as candidates for DG and Capacitor placement.

The DGs are taken to operate in PQ mode with a power factor of 1. They therefore produce only active power at the buses they are installed at. Reactive power is provided by the capacitors which are simultaneously placed at the candidate buses together with the DGs. In order to limit the maximum size of the capacitor, the power factor resulting from placement of both DG and capacitor is taken as 0.9.

Once the location for placement is identified, the next task is to identify the optimal size of the DGs and capacitors that will improve the voltage stability indices of the candidate buses without violating the system constraints. To identify the optimal size, Hybrid Evolution Programming (HEP) is used to search for the optimal sizes that maximizes the voltage stability indices. The results obtained are used to carry out load flow for the IEEE 33-bus radial network presented in [31]. Plots for VSI and voltage profile are made. All simulations were done using MATLAB.

Problem Formulation

The objective function for the placement problem is based on the Voltage Stability Index presented in [18]. The aim is placement of DGs and capacitors in radial distribution system so as to enhance voltage stability. The function to be maximized is:

$$f(VSI) = \sum_{i=2}^{n} VSI_i \tag{2}$$

where,

$$VSI_i = |V_s|^4 - 4V_s^2 \left(R_i P_{Li} + X_i Q_{Li}\right) - 4\left(X_i P_{Li} - R_i Q_{Li}\right)^2 \tag{3}$$

and

$i = 2,3,4,\ldots,n$

V_s is the source voltage

Q_{Li} is the total reactive power fed through node i

P_{Li} is the total active power fed through node i

R_i is the resistance between source bus and node i

X_i is the reactance between source bus and node i

Equation (2) is maximized subject to the following load flow equations and operational constraints.

Equality constraints

The equality constraints include non-linear recursive power flow equations formulated as follows:

$$P_{i+1} = \left[P_{i,i+1} - \left(R_{i,i+1} \frac{P_{i,i+1}^2 + Q_{i,i+1}^2}{|V_i|^2} \right) - P_{i+1}^L + \alpha_{P_{DG}} P_{i+1}^{DG} \right] \tag{4}$$

$$Q_{i+1} = \left[Q_{i,i+1} - \left(X_{i,i+1} \frac{P_{i,i+1}^2 + Q_{i,i+1}^2}{|V_i|^2} \right) - Q_{i+1}^L + \alpha_{Q_{QC}} Q_{i+1}^C \right] \tag{5}$$

and

$$|V_{i+1}|^2 = |V_i|^2 - 2\left(P_{i,i+1} R_{i,i+1} + Q_{i,i+1} X_{i,i+1}\right) + \left(P_{i,i+1}^2 + Q_{i,i+1}^2\right)\left(\frac{R_{i+1}^2 + X_{i+1}^2}{|V_i|^2} \right) \tag{6}$$

where,

$i = 1,2,3,\ldots,n$

P_{i+1} is active power through node $i+1$

Q_{i+1} is reactive power through node $i+1$
$|V_i|$ is the voltage magnitude at node i
$P_{i,i+1}$ is active power flow in the branch between node i and $i+1$
$Q_{i,i+1}$ is reactive power flow in the branch between node i and $i+1$
$X_{i,i+1}$ reactance of branch between node i and $i+1$
$R_{i,i+1}$ resistance of branch between node i and $i+1$
$\alpha_{P_{DG}}$ is the DG active power multiplier set to 1 where there is a DG and 0 where there is none
P_{i+1}^{L} is the active power load at node $i+1$
Q_{i+1}^{L} is the reactive power load at node $i+1$
$\alpha_{Q_{QC}}$ is the reactive power multiplier set to 1 where there is a capacitor and 0 where there is none
Q_{i+1}^{C} is the capacitor reactive power load at node $i+1$

Inequality Constraints
The inequality constraints include:

$$V_{i\,\min} \le V_i \le V_{i\,\max} \tag{7}$$

Voltage operational tolerance

Thermal capacity limit

$$|I_{i,i+1}| \le |I_{i,i+1}|_{\max} \tag{8}$$

Total DG capacity constraint which should be within a given penetration level

$$\frac{\sum_{i=1}^{n} P_{i+1}^{DG}}{P_{Load}} \le \eta \tag{9}$$

DG active power limits

$$0 \le P_i^{DG} \le P_{DG\max} \tag{10}$$

Capacitor reactive power limits

$$0 \le Q_i^{C} \le Q_{C\max} \tag{11}$$

The total number of buses for DG placement was determined using equation (12).

$$No.\,of\ DGs = \frac{\text{maximum DG penetration}}{\text{maximum DG size}} \tag{12}$$

The inequality constraints are enforced using the penalty function shown in equation (13).

$$PF = k\left(\sum_{i=1}^{n} h(V_i) + \sum_{i=1}^{n} h\left(P_i^{DG}\right) + \sum_{i=1}^{n} h\left(Q_i^{c}\right) + \sum_{i=0}^{n-1} h\left(\left|I_{i,i+1}\right|\right)\right) \tag{13}$$

where,
PF is the penalty function.
k is the penalty coefficient

$$h(x) = \begin{cases} \left(x - x^{\max}\right)^2 \text{ if } x > x^{\max} \\ \left(x^{\min} - x\right)^2 \text{ if } x < x^{\min} \\ 0 \text{ if } x^{\min} \le x \le x^{\max} \end{cases}$$

$x^{\min}$ is lower limit of variable x
$x^{\max}$ is upper limit of variable x

The penalty coefficient is usually taken as values between 10^3 and 10^6 [32].
The objective function therefore becomes:

$$f(VSI) = \sum_{i=2}^{n} VSI_i + PF \quad (14)$$

Table- 2 shows the parameters for the optimization problem.

Table- 2 Parameters for the optimization problem

Parameter	**Value**
Maximum DG penetration, η	50%
Maximum DG Size	500kW
Maximum voltage at a bus $\lvert V_i \rvert_{max}$	1.05p.u
Minimum voltage at a bus $\lvert V_i \rvert_{min}$	0.95p.u
Total network active power demand (IEEE-33 Bus)	3.715MW
Maximum DG penetration in kW (IEEE-33 Bus)	1857.5kW
No. of locations=Max. DG penetration/max. DG size (IEEE-33 Bus)	4

Load Flow

In order to calculate the initial network parameters, a load flow was done. The load flow technique used was the backward/forward sweep load flow method. In addition to the load flow, the voltage stability indices (VSI) for the network were calculated and a ranking done to determine the locations with lowest VSI that would be candidates for installation of DGs and capacitors. The load flow results and corresponding VSI are as shown in Table- 3.

Table- 3 Load flow data and VSI for IEEE-33 Bus Network

Bus No.	**Vbus (p.u)**	**VSI**	**Rank**		**Bus No.**	**Vbus (p.u)**	**VSI**	**Rank**
1	1	1	33		18	0.9036	0.669	1
2	0.997	0.9993	32		19	0.9965	0.938	27
3	0.983	0.9846	30		20	0.9929	0.986	31
4	0.975	0.9314	26		21	0.9922	0.972	29
5	0.968	0.9033	23		22	0.9915	0.969	28
6	0.949	0.8739	21		23	0.9792	0.915	24
7	0.946	0.8119	19		24	0.9725	0.919	25
8	0.932	0.7987	17		25	0.9692	0.894	22
9	0.926	0.7545	14		26	0.9474	0.817	20
10	0.92	0.7343	13		27	0.9448	0.805	18
11	0.919	0.7161	10		28	0.9334	0.796	16
12	0.918	0.7134	9		29	0.9251	0.759	15
13	0.911	0.7085	8		30	0.9216	0.732	12
14	0.909	0.6898	5		31	0.9174	0.721	11
15	0.908	0.6829	4		32	0.9164	0.708	7
16	0.906	0.6787	3		33	0.9161	0.705	6
17	0.904	0.6746	2					

From Table- 3, the buses that formed candidates for installation of DG and capacitor are 18, 17, 16 and 15 owing to their low VSIs.

Hybrid Evolution Programming

Hybrid Evolution programming algorithm used to obtain the optimal sizes of DGs and Capacitors is as shown in Fig. 1. The algorithm is explained in the following steps:

1. Representation of solution

Each trial solution is represented by the vector $S_P^T = [P_{Li} \quad Q_{Li}]$ where P_{Li} and Q_{Li} is the total active and reactive power, respectively, fed through node i .

2. Initialization

The values of V_s , R_{si} and X_{si} of equation (3) are constants. V_s is set to 1 whereas values of R_{si} and X_{si} are calculated. The initial population is initialized randomly using a random uniform number and limiting the value of each element of the individual to be between the upper and lower boundaries of each variable as shown in equation (15).

$$x_i = x_i^{\min} + u\left(x_i^{\max} - x_i^{\min}\right) \quad (15)$$

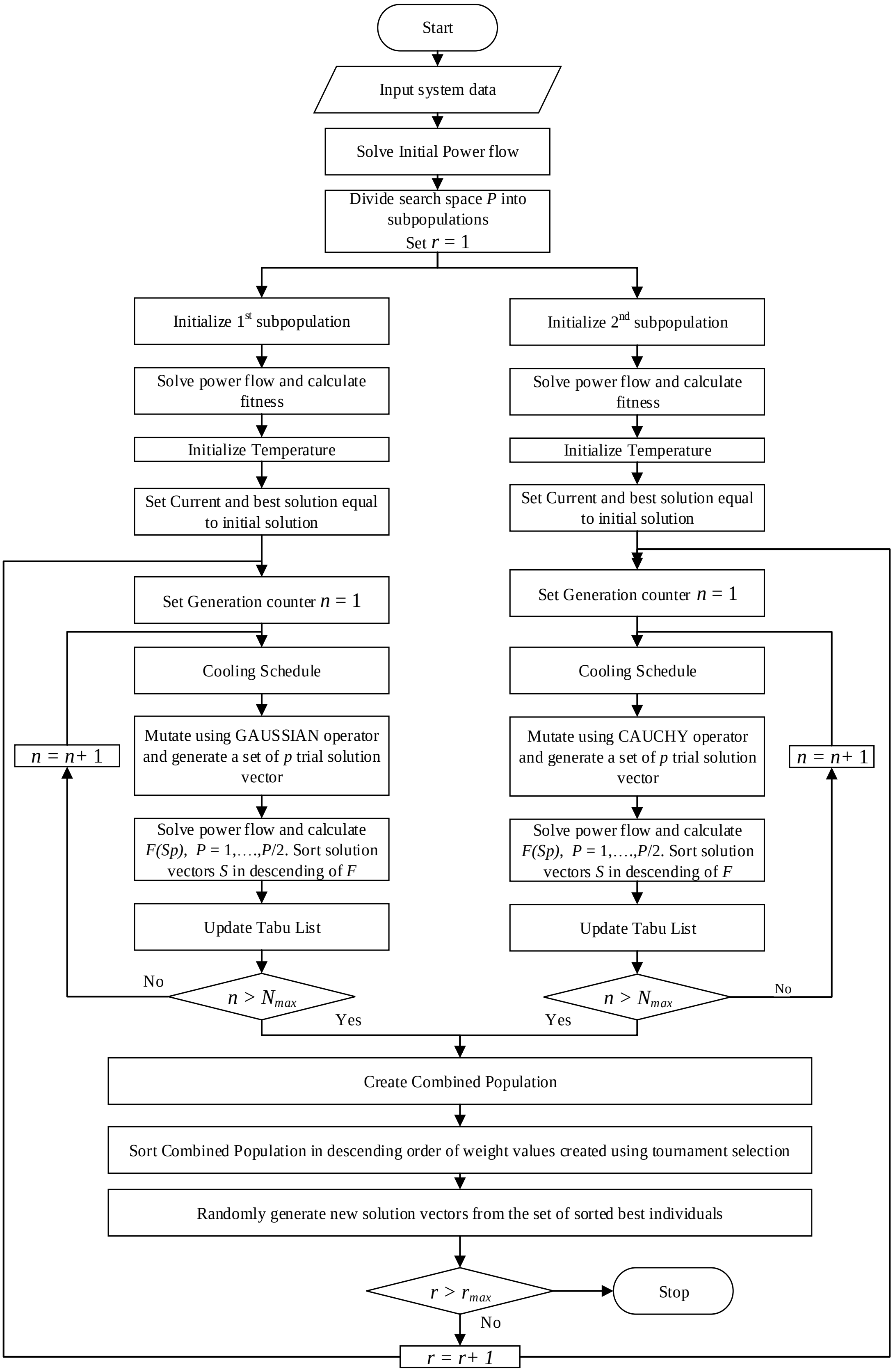

Fig. 1 Hybrid Evolution Programming Algorithm

3. Power Flow solution

Power flow is run to determine the values of injected active and reactive power at each bus. In addition, the line power losses and voltage at each bus are determined. The power flow method used is forward/backward sweep.

4. Fitness Calculation

The fitness is calculated from the objective function shown by equation(2)to determine the optimality of the candidate solution.

5. Cooling schedule

The initial temperature of each subpopulation is calculated using equation (16). This initial temperature is decreased using the simulated annealing cooling schedule in equation (17).

$$T_{0,m} = -\left(F_{\max,m} - F_{\min,m}\right)/\ln P_r \tag{16}$$

$$T_{r,m} = \lambda^{r-1} T_{0,m} \tag{17}$$

where $T_{0,m}$ initial temperature of the mth subpopulation, $F_{\min,m}$ objective value of the worst individual in the mth subpopulation, $F_{\max,m}$ objective value of the best individual in the mth subpopulation, P_r -Probability of accepting the worst individual with respect to the best individual, $T_{r,m}$ -annealing temperature of the mth subpopulation after the r^{th} reassignment, λ rate of cooling and r iteration counter of reassignment

6. Mutation

Two mutation operators are used to increase the diversity of the search. The two operators are Gaussian operator and Cauchy operator. The mutation operators are combined with the Cooling Schedule of Simulated Annealing. Each element of the offspring individual is calculated as shown in equation (18).

$$X'_{k,i} = X_{k,i} + \sigma_{k,i} * \xi_m \tag{18}$$

$$\sigma_{k,i} = T_{r,m} * a^{r-1} * \left(x_i^{\max} - x_i^{\min}\right) \tag{19}$$

where,

$X'_{k,i}$ - ith element of kth offspring individual, $X_{k,i}$ - ith element of kth parent individual, $\sigma_{k,i}$ -mutation step size for the ith element of the kth individual, ξ_m -mutation operator of the mth subpopulation which include $C(0,1)$ and $N(0,1)$, $C(0,1)$ is Cauchy random number with parameter $t = 1$, $N(0,1)$ is Gaussian random number with mean 0 and standard deviation of 1 and a - a positive number slightly less than 1.

7. Tabu list

The Tabu list is used to keep record of current best solutions. It has a finite length and stores the list of the current best solutions from the search process. The Tabu list is developed by replacing the worst solution in the list by a better solution in obtained during the search process. However, this Tabu restriction is overridden by the Acceptance Criterion of the Simulated Annealing if the Acceptance criterion is satisfied. The Acceptance Criterion is based on equation (20). The Tabu rule of replacing solutions in the finite Tabu List is overridden when a randomly generated variable in the interval [0,1] is less than the probability acceptance criterion.

$$P_{k,m} = 1 \Big/ \left(1 + \exp\left(-\Delta / T_{r,m}\right)\right) \tag{20}$$

where, $P_{k,m}$ is the probability acceptance criterion of the kth individual in the mth subpopulation, Δ is the difference between the objective value of the kth offspring and the corresponding parent individual and $T_{r,m}$ is the annealing temperature of the mth subpopulation after the r^{th} reassignment.

8. Reassignment strategy

In order for Hybrid Evolution programming to select individuals for the next population, the parents and offspring are combined. The individuals in the combined population compete with randomly selected individuals in the combined population for a chance to get selected. A weight value is assigned to an individual according to the competition as shown in equation (21).

$$w_i = \sum_{t=1}^{N} w_t \tag{21}$$

where, N is the population size, w_t is a number of $\{0,1\}$ which represents win, 1 or loss, 0 as p_i competes with a randomly selected individual p_r in the combined population. w_t is given by equation (22).

$$w_t = \begin{cases} 1 & f_i > f_r \\ 0 & otherwise \end{cases} \quad (22)$$

where, f_r is the fitness of a randomly selected individual p_r and f_i is the fitness of p_i. When all the individuals p_i, $i = 1,2,\cdots 2N$ get their competition weights, they are ranked in descending order of their corresponding w_i. The first N individuals are selected to be members of the next population together with corresponding fitness values f_i.

9. Termination criteria

The termination of the algorithm is determined by a set number of iterations or the convergence of solutions. The algorithm terminates when there is consistency of solutions or when maximum number of iterations is reached.

Hybrid Evolution Programming Parameters

Table- 4 shows the parameters used for the Hybrid evolution algorithm.

Table- 4 HEP Parameters

Parameter	Value
Population Size	200
Number of iterations	100
rate of cooling, λ	0.8
Probability of accepting the worst individual with respect to the best individual, P_r	0.3
a - a positive number slightly less than 1	0.95

RESULTS AND DISCUSSION

The hybrid evolution programming algorithm was used in the placement of DGs and capacitors in the IEEE 33-bus network. The placement was done on bus No. 15, 16, 17 and 18.Table- 5 shows the DGs and Capacitor sizes obtained using HEP algorithm.

Table- 5 DGs and Capacitor sizes obtained from HEP Algorithm

Bus No.	Size of DG(kW)	Size of Capacitor (kVAr)
15	15.96	92.19
16	300.6	35.62
17	285.39	422.73
18	428.4	361.37

The voltage and VSI values that resulted from the installation of DG and capacitor sizes, shown in Table- 5, in the IEEE-33 bus radial network are presented in Table- 6.

Table- 6 Voltage and VSI values after placement of DGs and Capacitors using HEP Algorithm

Bus No.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
Vbus (p.u)	1	0.998	0.989	0.985	0.981	0.973	0.974	0.975	0.98	0.985	0.986	0.988	0.998
VSI	1	1	0.9912	0.9566	0.9412	0.9254	0.8963	0.8999	0.9034	0.9221	0.9413	0.9451	0.9518

Bus No.	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
Vbus(p.u)	1.003	1.009	1.015	1.027	1.029	0.997	0.994	0.993	0.993	0.985	0.979
VSI	0.9917	1.0118	1.0361	1.0598	1.1124	1.1211	0.9879	0.9762	0.9723	0.9722	0.9409

Bus No.	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**
Vbus(p.u)	0.975	0.971	0.968	0.957	0.949	0.946	0.942	0.941	0.94
VSI	0.9185	0.9037	0.8889	0.8769	0.8382	0.811	0.8007	0.7874	0.7841

Voltage profiles showing comparison of voltages at all buses before and after DG and Capacitor placement were plotted. In addition, a comparison was made on voltage and VSI values at the buses where DGs and Capacitors were installed since they represented the highest voltage improvement in the entire radial distribution network.

Fig. 2 shows the Voltage and VSI profiles at all buses of the IEEE-33 bus radial distribution network before installation of DGs and Capacitors and after installation of DGs and Capacitors using values obtained from Hybrid Evolution Programming algorithm.

Fig. 2 Voltage and VSI profile comparison for IEEE-33 Bus radial distribution network

Fig. 3 shows comparison of voltage and VSI values at buses 15 to bus 18 where the DGs and capacitors were placed. These buses represented the buses with the greatest improvement in voltage stability.

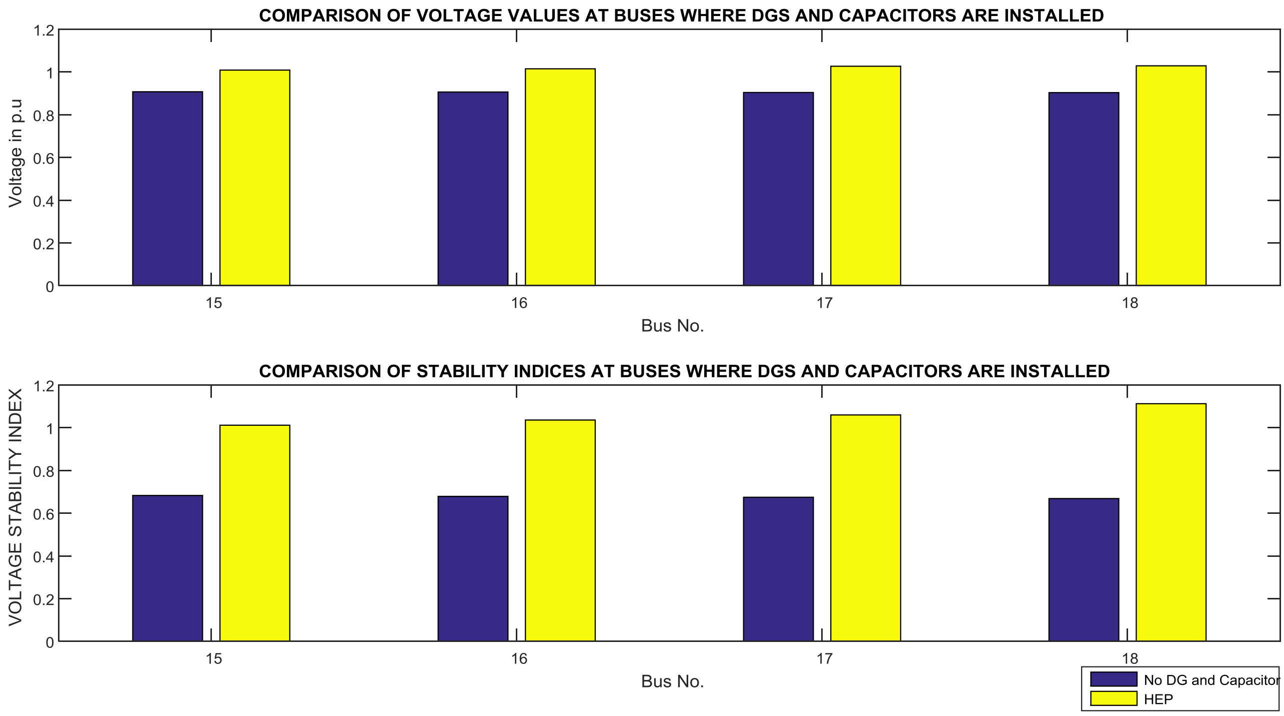

Fig. 3 A comparison of voltage and VSI at buses where DG and Capacitor were installed

The parameters used for analysis of voltage stability improvement are voltage values and voltage stability indices (VSIs). From the initial load flow, the minimum voltage for the IEEE 33-bus radial distribution network was 0.9036 while the minimum VSI was 0.6690.

The optimal values of DGs and Capacitors are indicated in Table- 5. After these optimal sizes of DGs and capacitors were placed in the IEEE 33-bus radial distribution system, the minimum voltage obtained was 0.9400 p.u whereas the minimum VSI was 0.7841. This represents a 4% improvement on minimum voltage and 17.2% on minimum VSI. In addition, the percentage improvement on the voltage and VSI at buses where DGs and capacitors were installed is shown in Table- 7.

Table- 7 Percentage improvement in voltage and VSI using HEP values

	Bus No.	**15**	**16**	**17**	**18**
Voltage	Before Placement in p.u	0.908	0.906	0.904	0.9036
	After Placement in p.u	1.009	1.015	1.027	1.029
	Percentage Improvement	11.1	12.0	13.6	13.9
VSI	Before Placement	0.6829	0.6787	0.6746	0.669
	After Placement	1.0118	1.0361	1.0598	1.1124
	Percentage Improvement	48.2	52.7	57.1	66.3

CONCLUSION

In this work, a novel way of optimally placing and sizing DGs and capacitors in radial distribution networks was developed. An objective function based on voltage stability index was successfully developed. The objective function was solved using Hybrid evolution programming. When the placement was done using this method, the values of minimum voltage for the network improved from 0.9036 to 0.9400p.u whereas the minimum VSI improved from 0.6690 to 0.7841 respectively. It can therefore be concluded that the values of DGs and capacitors obtained using HEP algorithm improved the voltage profile and voltage stability of the radial distribution network.

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