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Operation of distribution network with optimal placement and sizing of dispatchable DGs and shunt capacitors

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ABSTRACT

This paper presents a methodology for sustainable operation of the distribution network with optimal placement and sizing of dispatchable DGs and shunt capacitors. The objective of this work is aimed at reducing the feeder current drawn from the grid and minimizing the annual energy losses along with real power loss reduction and improvement of voltage profile. An average hourly variation of load demand profile is considered. Sensitivity analysis based on voltage stability index is used to obtain the location of dispatchable DGs and shunt capacitors. The size of the dispatchable DGs is optimized using GA optimization tool. Annual cost savings is computed to show the economic benefits of the operation. Effectiveness of the proposed methodology is demonstrated on a 33 node distribution network. The results demonstrate the effectiveness of the proposed methodology over other existing methods available in the literature.

1. Introduction

Distributed generation (DG) has become a very attractive option these days for integration into the power distribution systems due to their several advantages like voltage profile improvement, reduction in power losses with enhanced reliability and security [1,2]. DGs can support system voltage, reduce system losses, improve the reliability and security of the system, relieve distribution congestion and defer system upgradation [3]. Walling et al. [4] have discussed several issues related to power penetration by DGs into a distribution network. The problem of determining the optimal location and size of DG units has been an active research area for the past few years. It is aimed at the reduction of power losses, improvement of voltage profile and improvement of voltage stability of the distribution network. Proper placement and sizing of DG units are necessary to avoid power losses and overvoltage issues. Nara et al. [5] have formulated a methodology based on tabu search for optimal placement of distributed generators to minimize the distribution losses. Yammami et al. [6] have formulated an efficient hybrid multi-objective optimization algorithm using current injection based distribution load flow for optimal placement and sizing of DGs to improve voltage profile and minimize the power losses. Nekooei et al. [7] have presented the placement and sizing of DGs in radial distribution networks using an Improved Harmony Search algorithm and Novel Global Harmony search. The method presented in Ref. [7] has been compared with Non-dominated Sorting Genetic Algorithm II (NSGA-II) for the feasibility of the proposed method. Ameli et al. [8] have presented a multi-objective function based on multi-objective Particle Swarm Optimization (PSO) considering loss minimization, voltage improvement and economic analysis based on Distribution Company and DG owner's viewpoints. Elsaiah et al. [9] have proposed a methodology based on analytical method for solving the placement and sizing problem of DGs. The analytical method presented in Ref. [9] involves no convergence issues with systems having high R/X ratios and leads to optimal or near-optimal solution. Gampa and Das proposed the optimal placement and sizing of DGs using genetic algorithm (GA) considering average hourly variations of load [10]. Mohandas et al. have formulated a multi-objective performance index for improving the voltage stability using optimal placement and sizing of DGs using Chaotic Artificial Bee Colony algorithm [11]. Murty and Kumar have proposed power stability index and voltage stability index based heuristics methods for optimal placement of DGs considering the presence of load growth, combined load power factor and voltage stability margin [12]. Liu et al. [13] have presented a multi-objective planning problem for optimal sizing and placement of DGs using improved Non-Dominated Sorting GA II algorithm with time sequence characteristics of loads and DGs considering investment and operational cost of DGs, electricity purchasing cost from the main grid and minimum voltage deviation. Viral and Khatod [14] have presented an analytical approach

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Nomenclature

a	the quadratic coefficient of the quadratic equation
AS	annual energy savings
b	the linear coefficient of the quadratic equation
c	the constant or the free term of the quadratic equation
C	per unit cost of energy
CRF	cost recovery factor
D_1	capacitor purchase cost
D_2	capacitor installation cost
$DG_{\cos t}$	cost of per kW installation
DG_6	real power penetration by DG at node 6
f	fitness function
F	quadratic objective function of minimization type
$I_{\cos t}$	installation costs
$I(mm)$	current of branch 'mm'
I_t	target value of the feeder current which is set to 0.0001p.u.
$I_{(1,2)}$	feeder current of branch 1-2
$I(1,2)\_a$	feeder branch current after the placement of DG units
$I(1,2)\_b$	feeder branch current at nominal load level
k	integer
LL	normalized load levels
mm	branch number connecting node 'mm' and node '$mm+1$'
$M_{\cos t}$	maintenance costs
n	counter
ndg	number of DG units placed in the distribution network
nsc	number of shunt capacitors placed in the distribution network
N	number of years
N_{mm}	voltage stability index for node selection
N_{node}	node with the highest voltage stability index
$\mathrm{N_{pop}}$	population size
NB	Total number of buses/nodes in a network
$OM_{\cos t}$	maintenance charges to be paid annually
$P(mm+1)$	total real power fed through node '$mm+1$'
P^{after}	real power drawn by the network after the placement of DG unit and shunt capacitor banks
P^{before}	real power drawn by the network at nominal load
P_{dg}	real power supplied/generated by the biomass based DG unit
$P_{DG\cos t}$	installation cost of biomass based DG unit
P_{load}	total real power load of the network at nominal voltage load
P_{loss}	real power loss of the network
P_{loss_a}	real power loss after the placement of DG units
P_{loss_b}	real power loss of the distribution network at nominal load level
$P_{dg}^{\max}$	DG power installed in the network at peak load level
P_t	target term for real power which is set to the sum of the total real power load and real power loss
$P_1(mm+1)$	product of $P(mm+1)$and reactance of branch 'mm'
$P_2(mm+1)$	product of $P(mm+1)$and resistance of branch 'mm'
$Q(mm+1)$	total reactive power fed through node '$mm+1$'
$Q_{dg/sc}$	reactive power supplied by the DG units or shunt capacitors respectively
Q_{load}	total reactive power load of the network at nominal voltage load
Q_{loc}	number of capacitors installed at the obtained nodes/locations in the network
Q_{loss}	reactive power loss of the network
Q_t	target term for the reactive power which is set to the sum of the total reactive power load and reactive power loss
$Q_1(mm+1)$	product of $Q(mm+1)$and resistance of branch 'mm'
$Q_2(mm+1)$	product of $Q(mm+1)$and reactance of branch 'mm'
r	rate of interest per annum
$r(mm)$	resistance of branch 'mm'
S	total energy savings after the placement of DG units and shunt capacitor banks
SC	shunt capacitors
$SC_{i\cos t}$	shunt capacitor installation cost
$SC_{p\cos t}$	shunt capacitor purchase cost
SC_6	reactive power penetration by shunt capacitor at node 6
T_n	number of hours in a year corresponding to a particular load level
$V(mm)$	voltage magnitude of node 'mm'
$V(mm+1)$	voltage magnitude of node '$mm+1$'
V_i	voltage magnitude at the i^{th} node, for $i = 1, 2, 3 \ldots$ NB
$V_{\min a}$	minimum voltage magnitude of the network after the placement of DG units
$V_{\min b}$	minimum voltage magnitude of the network at nominal load level
$x(mm)$	reactance of branch 'mm'

based on active and reactive components of branch currents and aimed at loss minimization using optimal placement and sizing of DGs. Gonzalez et al. [15] have introduced a hybrid methodology using discrete particle swarm optimization and optimal power flow for optimal placement and sizing of the DGs. The proposed method in Ref. [15] has been compared with other methods available in literature and is seen to provide better solutions than genetic algorithm. Moradi and Abedini [16] have developed a combination of genetic algorithm and particle swarm optimization for optimal placement and sizing in distribution networks. Multi-objective optimization models have been formulated in several literature [17–20]. Moravej and Akhlaghi [21] have proposed a methodology based on cuckoo search algorithm for optimal placement and sizing of DG in the distribution network. The cuckoo algorithm in Ref. [21] has been compared with genetic algorithm and particle swarm optimization techniques to investigate its effectiveness. Aman et al. [22] have proposed a technique for simultaneous placement and sizing of DGs in the network using hybrid particle swarm optimization. Hung et al. [23] have proposed the optimal placement and sizing in distribution networks considering dispatchable and nondispatchable DGs. In the present work, only dispatchable DGs (biomass) are considered. Murthy and Kumar [24] have presented a comparison of various DG allocation methods for optimal placement in radial distribution network. Uniyal and Kumar [25] have presented the optimal placement of DGs using the comparison of four different techniques. Bohre et al. [26] have used a combination of GA and PSO using load models for optimal placement and sizing of DGs in distribution networks. Optimal placement and sizing of DGs has also been carried out using biogeography based algorithm and adaptive quantum inspired evolutionary algorithm [27,28]. Kirthiga et al. [29] have proposed a methodology for autonomous operation of the existing distribution network with optimal placement and sizing of DGs using GA and PSO. A review paper presented by Jordehi demonstrated that proper allocation of DGs could enhance the reliability and decrease the investment and operational costs [30]. The review work presented in Ref. [30] identifies the research gaps and recommends helpful suggestions for future research on DG allocation.

Research work focused on shunt capacitors gained importance during the last decade of the 20th century. Shunt capacitors have been used in the distribution networks for reducing the energy losses and improving the voltage profile [31–34]. Baran and Wu started the capacitor placement problem for peak power loss reduction using a mixed integer programming problem [31]. Chiang et al. [32] have presented the capacitor problem for power loss minimization using the technique of simulated annealing. The capacitor problem in Ref. [32] considers the practical aspects of capacitors when placed in a radial distribution network at different load levels. Das [33] incorporated the fuzzy-GA technique for optimal capacitor placement to improve the voltage profile and the annual net savings. Park et al. [34] have formulated a methodology using genetic algorithm to minimize the power loss in the network and also minimize the installation costs of the capacitors when optimally placed in the distribution network. Swarnkar et al. [35] have developed a methodology for optimal placement of fixed and switched capacitors using genetic algorithms. El-Fergany and Abdelaziz [36] have formulated an artificial ant colony based approach to minimize the power loss, improve the voltage stability index and to determine the minimum VAr injection required in the distribution network to achieve the desired objectives. Nojavan et al. [37] have proposed the capacitor placement problem for radial and meshed networks using a mixed integer non-linear programming problem. The problem stated in Ref. [37] is capable of solving large scale networks. Sultana and Roy [38] have presented Teaching Learning based algorithm (TLBO) for power loss minimization and cost reduction for capacitor placement in distribution network. The proposed method in Ref. [38] has been compared with other methods for the solution feasibility. Chang and Lern [39] have formulated a strategy based on tabu search for optimal placement of shunt capacitors resulting in optimum savings. Krishnamurthy and Mohlwini [40] have presented the optimal placement of shunt capacitor based on voltage stability index method using real-time digital simulator. Dixit et al. [41] have presented an approach based on loss sensitivity factor to identify the optimal locations and particle swarm optimization technique for optimal sizing of shunt capacitors. The objective in Ref. [41] is also aimed at power factor improvement and net savings after the shunt capacitor placement. Mosbah et al. [42] have formulated an objective for optimal placement and sizing of shunt capacitors and have applied this methodology on a real network of Algerian distribution network. Aman et al. [43] have presented a review study of the optimum shunt capacitor placement. The paper in Ref. [43] has presented the capacitor placement problem using six different algorithms present in the literature and finally has been compared with particle swarm optimization (PSO).

Research works focused on distributed generations and shunt capacitors together have come up in the literature too. Gunda and Khan [44] have formulated a differential evolutionary algorithm for productive solution using DGs and shunt capacitors. Kalantari and Kazemi [45] have used genetic algorithm for successful placement of distributed generation unit and shunt capacitor in the distribution network for real power and reactive power loss reduction and improvement of voltage profile. Wang and Zhong [46] have used heuristics method to improve the voltage profile. Karami et al. [47] have used genetic algorithm for optimal location and sizing of DGs and shunt capacitors considering loadability. Hooshmand and Mohkami have used particle swarm optimization for the same [48]. Zeinalzadeh et al. [49] have proposed a multi-objective optimization problem for simultaneous placement of shunt capacitors and DGs considering load uncertainty using multi-objective particle swarm optimization. Sajjadi et al. [50] have used memetic algorithm (local search and genetic algorithm) for real power loss reduction and voltage profile improvement using simultaneous placement of distributed generation and shunt capacitors. Naik et al. [51] have used analytical method for loss reduction. Khan et al. [52] have used binary collective animal behavior optimization algorithm for minimization of line losses and minimization of voltage deviation in the distribution network. The main aspects of the reviewed

Table 1
Main aspects of the literature review.

Reference No.	Objective Function	DG Sizing Optimization Technique	Shunt Capacitor Sizing Optimization Technique	Zero Power drawn from the main grid
[5]	LR[a]	Tabu Search	–	–
[6]	LR, VPI[a]	Shuffled Bat Algorithm	–	–
[7]	LR, VPI	Improved Harmony Search Algorithm	–	–
[8]	LR, VPI, EA[a]	Mulitobjective PSO	–	–
[9]	LR	Analytical	–	–
[10]	LR, VPI, EA	GA	–	–
[11]	VS[a]	Chaotic Artificial Bee Colony	–	–
[12]	VS	Heuristics	–	–
[13]	EA, VD[a]	Improved NSGA II	–	–
[14,23]	LR	Analytical	–	–
[15,22]	LR	Discrete PSO	–	–
[16]	LR	GA & PSO	–	–
[17–20,24,27,28]	LR	Heuristics	–	–
[21]	LR	Cuckoo Algorithm	–	–
[25]	LR	Cuckoo Search, Gravitational Search, GA, PSO	–	–
[26]	LR, VPI, EA	GA & PSO	–	–
[29]	LR, VPI, EA	GA, PSO	–	Yes
[53]	LR, VPI	GA	–	Yes
[31,37]	LR	–	Mixed integer Prog.	–
[32]	LR	–	Simulated Annealing	–
[33]	VPI, EA	–	Fuzzy-GA	–
[34,35]	LR, VPI	–	GA	–
[36]	LR, VS	–	Artificial Ant based Colony	–
[38]	LR, EA	–	TLBO	–
[39]	LR, EA	–	Tabu Search	–
[40]	LR, VS	–	Heuristics	–
[41,42]	LR, VPI, EA	–	PSO	–
[43]	LR	–	PSO	–
[44]	LR	Differential Evolutionary Algorithm		–
[45,47]	LR, VPI	GA		–
[46,52]	VPI	Heuristics		–
[48,49]	LR, VS	PSO/Multiobjective PSO		–
[50]	LR, VPI	Memetic Algorithm (Local Search + GA)		–
[51]	LR	Analytical		–

[a] LR = Loss Reduction, VPI = Voltage Profile Improvement, EA = Economic Analysis, VS = Voltage Stability, VD = Voltage Deviation.

literature have been summarized in the form of a table and are presented in Table-1.

From Table 1, it could be seen that most of the methodologies available in the literature are focused on improving the voltage profile and reducing the real power losses. Very few works can be found in the literature that aimed at satisfying more objectives other than the one stated above. Kirthigha et al. [29] have proposed a methodology for transforming the network into an autonomous microgrid. However, hourly varying load profile has not been considered in Ref. [29]. Meanwhile, Das et al. [53] have presented a quadratic objective function to draw zero power from the grid. The methodology in Ref. [53] is demonstrated on a 69 node distribution network considering monthly variations of load and the problem is optimized using genetic algorithm. The work done in Ref. [53] is further modified, elaborated and is presented in this paper with its overall technical and economic benefits. The average hourly load variations are considered in this paper along with a modified quadratic objective function. Moreover, research articles based on zero power drawn from the grid, due to the combination placement of DGs and shunt capacitors under average hourly loading conditions in the distribution network, has so far not been reported. In this paper, a modified quadratic objective function is proposed for the sustainable operation of the distribution network by drawing negligible power from the grid under average loading conditions and at the same time, improving the voltage profile and reducing the real and reactive power losses. The cost analysis for the same is also carried out further. The objective function defined in this paper is capable of producing better results than that available in the literature.

Although the distribution network draws negligible power from the grid, it remains connected to the grid. The frequency shall be dictated by the main grid and the DGs are synchronized with the grid frequency. If any DG fails, the back-up power will come from the grid and the reliability of the service provided by the utility to the customer could be maintained. The proposed methodology in this work is realized using proper placement of dispatchable DGs (biomass) and shunt capacitors.

The main features of this work are:

- Sustainable operation of the distribution network by minimizing the power losses, improving the voltage profile and drawing negligible power from the grid.
- Minimizing the annual energy losses and thereby maximizing the annual energy savings.
- The entire power of the loads and the losses is supplied by the dispatchable DGs and the shunt capacitors.
- Sensitivity analysis based on voltage stability index is considered for finding the optimal location of dispatchable DG units and shunt capacitor banks.
- The economic aspects of the proposed sustainable operation of the distribution network are examined with the help of cost benefit analysis.

The main motivation of this work is sustainable operation of the distribution network by using combination of unity power factor DGs and shunt capacitors. DGs operating at unity power factor and shunt capacitors are optimized to supply the total real and reactive power load along with the real and reactive power losses. At the same time, DGs operating at lagging power factor (without shunt capacitors) are also considered to perform the same objective. Emphasis is given on minimization of real and reactive power losses, improvement of voltage profile and negligible feeder current drawn by the network from the grid. All these conditions are met subject to the voltage and the branch current capacity constraints within limits.

2. Load modeling

An average hourly variation of load profile has been created based on IEEE RTS 96 system for load profile analysis [54]. The 24 h daily pattern presented in IEEE RTS 96 system is normalized and divided in load levels ranging from 0.4 to 1.0 p.u. A 33 node distribution network (Fig. 1) is considered for this purpose. The load profile is divided into 24 h with every hour being assigned a load value. The load value is a fraction of the peak load considered in this work. This pattern is considered for an entire year (8760 h). The average daily load demand model is presented in Table 2 and Fig. 2 presents the daily load pattern on an hourly basis. The peak load and minimum load are taken to be 1.0 p.u. and 0.4 p.u. respectively.

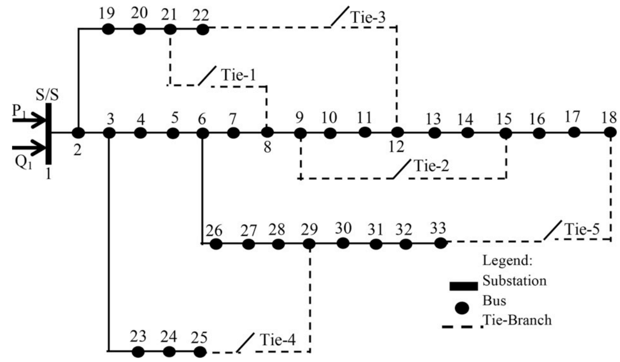

Fig. 1. A 33 node distribution network.

3. Node selection for DG placement

The sensitivity analysis approach is used for node selection. In this work, the node selected for DG placement must be capable of satisfying the desired objectives of reducing the power loss and maintaining the voltage profile. The sensitivity index parameters considered in this paper can be well explained with the help of the electrical equivalent of branch 'mm' as shown in Fig. 3.

In the equivalent representation, the branch 'mm' connects node 'mm' to '$mm + 1$'. '$P(mm + 1)$', '$Q(mm + 1)$', and '$V(mm + 1)$' are the real and reactive power fed through the node '$mm + 1$' and the voltage magnitude at node '$mm + 1$' respectively.

From the equivalent circuit diagram (Fig. 3), one can write [55].

$$I(mm) = \frac{V(mm) - V(mm+1)}{r(mm) + jx(mm)} \tag{1}$$

$$P(mm+1) - jQ(mm+1) = V(mm+1)^{*}I(mm) \tag{2}$$

From Eqs. (1) and (2), one can write,

$$\begin{aligned} &|V(mm+1)|^4 - \{|V(mm)|^2 - 2P(mm+1)r(mm) \\ &- 2Q(mm+1)x(mm)\}\,|V(mm+1)|^2 \\ &+ \{P^2(mm+1) + Q^2(mm+1)\}\{r^2(mm) + x^2(mm)\} = 0 \end{aligned} \tag{3}$$

Table 2
Average hourly daily load model.

Time	Load Level (p.u.)	Duration (hours)	Hours/year
12-1 am	0.5	1	365
1–6	0.4	5	1825
6–7	0.5	1	365
7–8	0.6	1	365
8–10	0.8	2	730
10–11	0.9	1	365
11-12 noon	1.0	1	365
12-1 pm	0.9	1	365
1–5	0.8	4	1460
5–7	0.9	2	730
7–9	1.0	2	730
9–10	0.8	1	365
10–11	0.7	1	365
11–12	0.5	1	365

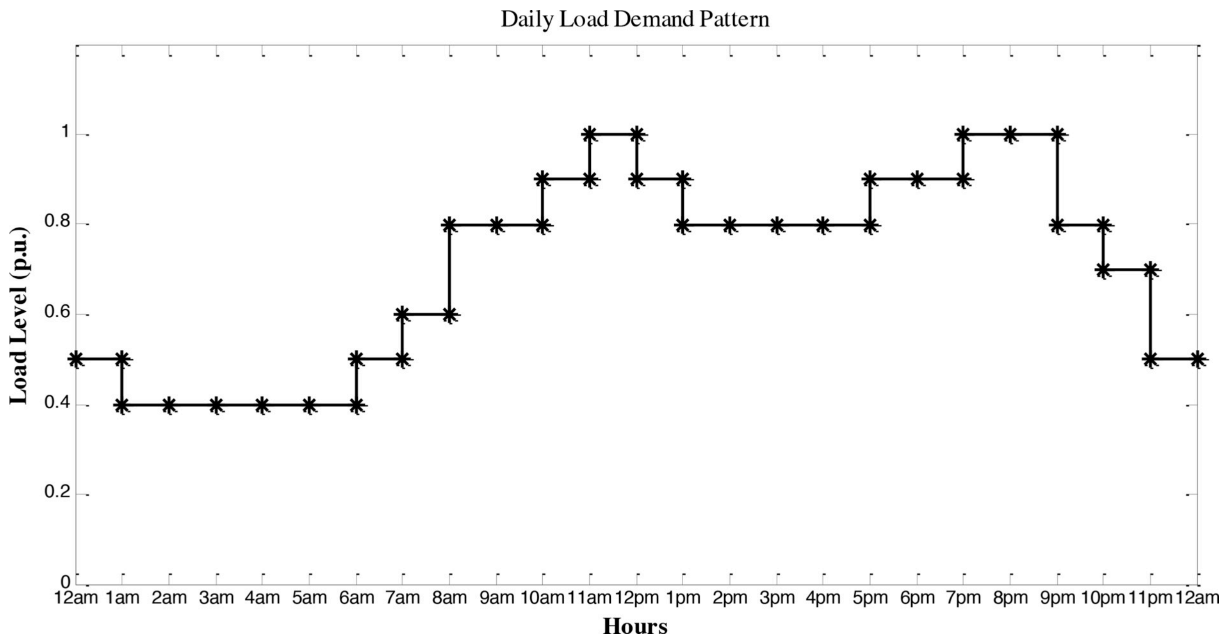

Fig. 2. Daily load demand pattern.

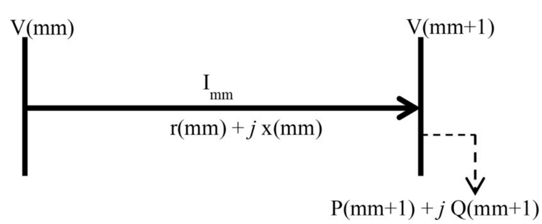

Fig. 3. Equivalent circuit diagram.

Equation (3) can be represented as a quadratic equation having the form,

$$ax^2 + bx + c = 0$$

If $a = 1$,

$$b = |V(mm)|^2 - 2P(mm+1)r(mm) - 2Q(mm+1)x(mm)$$

and

$$c = (P^2(mm+1) + Q^2(mm+1))(r^2(mm) + x^2(mm))$$

Then,

$$|V(mm+1)|^4 - b.\ |V(mm+1)|^2 + c = 0 \tag{4}$$

Equation (4) is quadratic of $|V(mm+1)|^2$, hence for real solution of$|V(mm+1)|^2$,

$$(-b)^2 - 4.\ a.\ c \geq 0 \tag{5}$$

Upon further simplification of Eq. (4), the equation takes the form,

$$|V(mm+1)|^4 \geq 4[P_1(mm+1) - Q_1(mm+1)]^2 + 4[P_2(mm+1) + Q_2(mm+1)]\ |V(mm+1)|^2 \tag{6}$$

Equation (6) is finally represented as,

$$N_{mm} = \frac{4\{P_1(mm+1) - Q_1(mm+1)\}^2 + 4\{P_2(mm+1) + Q_2(mm+1)\}^2 |V(mm+1)|^2}{|V(mm+1)|^4} \tag{7}$$

where

$$P(mm+1) = \mathrm{Re}\{V^*(mm+1).\ I(mm)\}$$

and

$$Q(mm+1) = -\mathrm{Im}\{V^*(mm+1).\ I(mm)\}$$

The voltage stability index is given by 'N_{mm}' and is expressed as presented in Eq. (7). The voltage stability index (N_{mm}) is ≤1 as obtained from Eq. (6). The node at which 'N_{mm}' is maximum is more sensitive to voltage collapse. The scope for improving the voltage stability of the distribution network lies at these nodes. Hence, the nodes with higher voltage stability index are considered for DG units and shunt capacitors placement. Once the sensitivity index 'N_{mm}' is obtained for all the nodes (Node 1 is considered as substation), the stability index values are arranged in descending order, and we define

$$N_{node} = \max(N_{mm}),\ mm = 2,3 \ldots NB$$

The node with the highest voltage sensitivity index is suitable for optimal location of DG placement. The ranking of nodes for 33 node distribution network under various load levels using the voltage stability index analysis is carried out and presented in Table 3. It has been found out that the node rankings for the optimal nodes remain the same under different load levels scenarios. Seven load levels ranging from 0.4 p.u. to 1.0 p.u. have been considered. Under each load level, the top five nodes in descending order of their N_{mm} values are nodes 6, 3, 28, 29 and 4. The voltage stability index value for all the nodes at 1.0 p.u. load level is presented in Fig. 4.

4. Proposed objective function

4.1. Methodology

As previously discussed in the Introduction, the main motivation of this work is sustainable operation of the existing distribution network by minimizing the power losses, improving the voltage profile and by drawing negligible feeder current from the grid. Hence, a quadratic objective function of the minimization form is considered for the

Table 3
Ranking of nodes.

Load levels (p.u.)	*Nodes*				
	1st	*2nd*	*3rd*	*4th*	*5th*
0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0	6	3	28	29	4

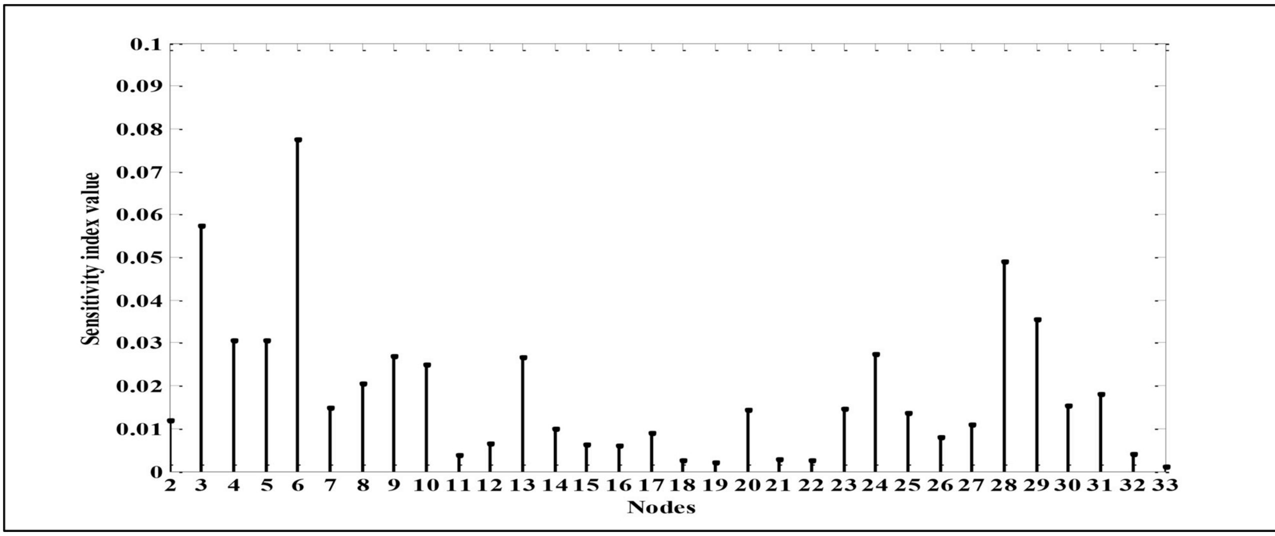

Fig. 4. Sensitivity Index Value at 1.0 p.u. load level.

proposed methodology. The proposed objective function considered in this paper involves target values of the real and reactive power to be supplied by the DGs and shunt capacitors placed in the distribution network. The target value for the real power is the total real power loads of the network at a particular load level along with the real power loss of the distribution network. The target value for the total reactive power is the total reactive power load of the network at a particular load level and its corresponding reactive power loss. The real and reactive power supplied by the DG units and the shunt capacitors respectively is aimed at supplying the target values of the real and reactive powers. At the same time, emphasis is given to maintain the voltage profile of the network. In order to maintain a smooth voltage profile, the voltage term is considered to be a quadratic function. Finally, the feeder current component $I_{(1,2)}$ is also included in the proposed objective function to minimize the value of feeder current drawn by the distribution network. Taking into account these desired objectives; the proposed objective function is mathematically formulated as given in Eq. (8).

Minimize

$$F = \left(\sum_{n=1}^{ndg} P_{dg} - P_t\right)^2 + \left(\sum_{n=1}^{nsc} Q_{dg/sc} - Q_t\right)^2 + (V_i - 1.0)^2 + (I_{(1,2)} - I_t)^2 \tag{8}$$

where

$$P_t = \sum P_{load} + P_{loss} \tag{9}$$

$$Q_t = \sum Q_{load} + Q_{loss} \tag{10}$$

The proposed objective function is aimed at sustainable operation of the distribution network by optimal placement of dispatchable DGs and shunt capacitors. The dispatchable DG considered in this work is biomass which is made to operate at unity power factor and lagging power factor. The power factor of the DG is taken to be the load power factor [20]. The shunt capacitors inject reactive power to the network. To satisfy the desired objectives, two cases (Case A and Case B) are being analyzed.

i. DGs operating at lagging power factor (lpf)
ii. DGs operating at unity power factor (upf) with shunt capacitors.

4.2. Optimization

The genetic algorithm optimization tool is considered here. Genetic algorithm is an evolutionary optimization technique which begins its search for solution within its multi-dimensional search space and proceeds towards the optimal solution using the concepts of selection, crossover, mutation and elitism. GA is based on the concepts of natural selection and genetics. GA can efficiently handle constrained and unconstrained optimization problems. GA is capable of overcoming the local optima and proceeds towards the global optimum. GA often proceeds in the direction of maximization of the fitness function. In this work, GA is used to solve the proposed multi-objective function as defined in the methodology. The optimal sizes of the dispatchable DG units and shunt capacitors banks are determined using GA. The sizes of the DG units and shunt capacitor banks are optimized at locations obtained in Section III. In GA, the 'fitness' function is defined as a non negative figure of merit which is to be maximized and is associated with the objective function. The objective function presented in Eq. (8) is of minimization type with the quadratic objective function 'F' being always positive. Hence, in order to satisfy both the conditions (i.e., non negative figure of merit to be maximized and always positive), the inverse of 'F' is considered [56].

The fitness function defined is given by.

Maximize

$$f = \frac{k}{F} \tag{11}$$

where 'k' is a small integer and 'F' is the minimization quadratic objective function defined in Eq. (8). Here, 'k' being a constant multiplier, the value of 'k' helps in adjusting the 'fitness' function in a close range of decimal places.

The optimum sizes are obtained for different load levels corresponding to different hours in a particular day. The flowchart for the objective function optimization is presented in Fig. 5.

5. Results and discussions

The daily hourly average load model discussed in Section II (Table 2) is considered for analysis. A 12.66 kV, 33 node distribution network (Fig. 1) with a real power load of 3715 kW and a reactive power load of 2300 kVAr is considered for the load model pattern discussed. The cost benefit analysis is studied in Section 6.

5.1. Operation of distribution network for drawing negligible power from the grid

For the network to draw negligible power, the real and reactive

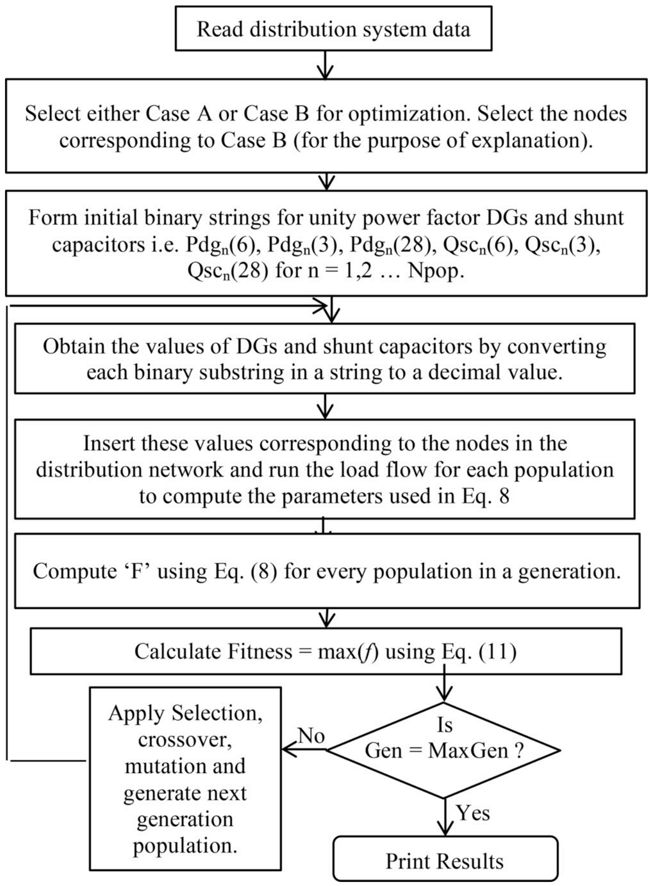

Fig. 5. Flowchart for objective function optimization.

power drawn by the network from the grid should decrease. In other words, the feeder current $I_{(1,2)}$ of the network must reduce to negligible value. The technical and economic aspects of the proposed methodology are demonstrated using the following two cases:

5.1.1. Dispatchable DG units operating at 0.84 lagging power factor (Case A)

The biomass based DG units are located at nodes 6, 3, 28 and the DG values are optimized using GA. The placement of DGs operating at lpf is carried out in three configurations. The first configuration comprises of a DG at node 6, the second comprises of nodes 6 and 3 whereas the last comprises of nodes 6,3,28. The analysis has been carried out for all load levels during the 24 h interval.

Table 4 presents the optimum values of DG units operating at a lagging power factor of 0.84 for all load levels. The DG values are optimized using GA for the three configurations stated above. Table 5 shows the real power loss and the feeder branch current at various load levels before and after the placement of DG units. It also presents the base real power loss and base feeder current drawn by the network for all load levels. It has been found in almost all the cases that the real power loss and the feeder current drawn by the network are considerably reduced. In case of DG placement at nodes 6, 3 and 28, significant improvements are seen in terms of power loss and feeder current drawn as compared to the other two configurations.

Table 6 presents the comparison of the DG unit values at load level 1.0 p.u. for all the three sets. The real power loss and the feeder current drawn by the network are compared in the given table. The proposed method shows a 78% reduction in power loss as compared to 72% in the existing method for configuration 3. At the same time, the feeder current drawn by the network has dropped to 0.00007 p.u. from 0.0461282 p.u. (Table 5). in the proposed method for placement of DG units at nodes 6,3,28.

5.1.2. Dispatchable DG units operating at upf with shunt capacitors (Case B)

In this case, an attempt is made to draw negligible power from the grid using a combination of DG units operating at unity power factor and shunt capacitors. The locations of the shunt capacitors are considered the same as that of the DG units. The multi-objective optimization is carried out at all load levels for 24 h. Similar to Case A, the optimization of DG units and shunt capacitors is carried out in 3 configurations at locations 6, 3, 28. Capacitor banks of 50 kVAr are used in this work [33].

Table 7 presents the optimum values of DG units and shunt capacitor banks placed in the network. The DG units are operating at unity power factor. Same trend has been observed as that seen in Case A for DG unit placement operating at 0.84 lagging power factor. Table 8 shows the real power loss and the feeder current drawn by the network after the placement of DG units and shunt capacitors. The feeder current drawn by the network at all load levels have been found to be negligible in all the three configurations.

Table 9 presents the comparison of the placement of the DG unit operating at unity power factor and the shunt capacitor with an existing method [49] at load level 1.0 p.u. The proposed method gives a power loss of 43.6 kW as compared to 80.8 kW in the method discussed in Ref. [49]. The shunt capacitor banks in the proposed method are placed on the same nodes where the DGs are placed.

Table 10 presents the minimum voltage magnitude of the network after the placement of DG units and shunt capacitors in Cases A and B. The base minimum voltage at load level 1.0 p.u. is found to be 0.9131 p.u. at node 18 which improves to 0.9883 at node 25 for configuration 1 in Case A. For configuration 1 in Case B, the voltage improves to 0.9884 p.u. at node 25. Configurations 2 and 3 show the similar trends. The minimum voltage magnitude improves to 0.9954 at node 25

Table 4
Sizing of DG units operating at 0.84 power factor.

	Node Locations					
Configurations	1	2		3		
Load Level	DG_6 (kVA)	DG_6 (kVA)	DG_3 (kVA)	DG_6 (kVA)	DG_3 (kVA)	DG_{28} (kVA)
0.4	1762.383	1131.1380	627.9488	551.2682	744.4980	459.0036
0.5	2210.883	1048.1894	1163.992	902.2312	819.1006	470.7080
0.6	2660.970	1904.4141	748.8122	1152.135	988.4334	498.9166
0.7	3110.446	1614.1849	1476.119	640.5483	1218.544	1242.053
0.8	3560.900	1929.5789	1617.090	1314.982	1159.616	1058.914
0.9	3997.070	2920.3877	1075.228	1500.656	1721.122	748.3137
1.0	4451.566	2503.9640	1939.283	1014.789	2039.398	1368.874

Table 5
Effect of DG units on real power loss and feeder current drawn by the network.

Load Level	Ploss_b (kW)	I(1,2)_b (p.u.)	Node Locations					
			Configuration 1		Configuration 2		Configuration 3	
			6		6,3		6, 3, 28	
			Ploss_a (kW)	I(1,2)_a (p.u.)	Ploss_a (kW)	I(1,2)_a (p.u.)	Ploss_a (kW)	I(1,2)_a (p.u.)
0.4	29.7162	0.0178342	13.6998	**0.0000271**	**8.9508**	**0.0000059**	**6.6838**	**0.0000166**
0.5	47.0708	0.022412	21.4739	0.0000185	14.7224	0.0000892	10.6332	0.0000631
0.6	68.7376	0.0274159	30.9853	0.0000274	21.1238	0.0000521	15.6194	0.0000253
0.7	94.9114	0.0317253	42.178	0.0000403	28.247	0.0000504	22.1676	0.0000974
0.8	125.8031	0.0364658	55.0743	0.0000646	36.7014	0.0000613	27.7233	0.0000402
0.9	161.6418	0.0412658	69.1918	0.0002322	48.4087	0.0000577	35.6589	0.0000892
1.0	202.6771	0.0461282	**85.5098**	**0.0002732**	**57.5409**	**0.0000893**	**43.5694**	**0.0000758**

Table 6
Comparison of DG unit placement for drawing negligible power from the grid at load level 1.0.

No. of DG units		*Proposed Method*			*Method in Ref. [29]*		
1	Node Locations	6			6		
	Size (MVA)	4.4516			4.9604		
	Base case loss (kW)	202.6771			202.6771		
	Power loss (kW)	**85.5097**			**116.4**		
	I(1,2) in p.u.	**0.0002732**			**0.006761**		
	% loss reduction	57.8099			42.5687		
2	Node Locations	6	3		3	29	
	Size (MVA)	2.5039	1.9393		3.6802	1.4089	
	Base case loss (kW)	202.6771			202.6771		
	Power loss (kW)	**57.5409**			**61.0**		
	I(1,2) in p.u.	**0.0000893**			**0.007297**		
	% loss reduction	71.6096			69.9028		
3	Node Locations	6	3	28	3	9	31
	Size (MVA)	1.0148	2.0394	1.3689	2.2267	1.1172	1.986
	Base case loss (kW)	202.6771			202.6771		
	Power loss (kW)	**43.5694**			**56.1**		
	I(1,2) in p.u.	**0.0000758**			**0.008901**		
	% loss reduction	78.5030			72.3205		

(Configuration 1, Case A) and 0.9953 at node 25 (Configuration 1, Case B) from 0.9669 p.u. at load level 0.4 p.u. Fig. 6presents the graphical representation of minimum voltage magnitudefor 24 h daily average load using configuration 3 (Cases A and B). The 24 h daily load demand model and pattern are presented in Table 2 and Fig. 2 respectively. V_{minb} and V_{mina} are the minimum voltage magnitudes before and after the placement of DG units and shunt capacitors. For Cases A and B, the minimum voltage magnitude at every hour is above 0.96 p.u. The figures shows that both Cases A and B are close and are considerably better than the base case.

Fig. 7 presents the graphical representation of the feeder substation current for the 24 h daily average load profile using configuration 3 (Cases A and B). The network draws negligible power from the grid for Cases A and B after the placement of DG unit and shunt capacitor as compared to the substation current drawn from the network before the placement of DG units and shunt capacitors. The substation feeder current drawn by the network in Cases A and B is close to zero as shown in Fig. 7.

6. Cost benefit analysis

The economic aspects of the placement of DG units and shunt capacitor banks are discussed in this section. The annual energy savings result in annual economic benefits. The saving depends on the reduction of power drawn by the network from the grid. Eventually, it depends on the substation feeder current drawn by the network. The expenditure includes the installation costs of the DG units and shunt capacitor banks. There are expenses associated with the maintenance

Table 7
Sizing of DG units and Shunt Capacitor banks.

Load Level	*Configuration 1*		*Configuration 2*				*Configuration 3*					
	DG_6[a]	SC_6 **	DG_6[a]	SC_6 **	DG_3[a]	SC_3 **	DG_6[a]	SC_6 **	DG_3[a]	SC_3 **	DG_{28}[a]	SC_{28} **
0.4	1497.423	900	945.711	600	547.111	300	414.183	500	600.437	150	470.669	250
0.5	1870.949	1150	1011.274	550	869.741	600	619.465	450	814.539	450	427.711	250
0.6	2252.589	1400	1112.442	1200	1137.060	200	1035.762	600	850.130	550	356.918	250
0.7	2633.399	1650	1506.326	850	1130.458	750	830.622	350	1223.884	450	576.403	800
0.8	3015.039	1900	1632.398	1000	1391.215	850	1295.999	700	1221.550	500	476.441	650
0.9	3399.792	2100	1803.274	1550	1596.030	550	1193.495	800	1416.364	900	762.035	400
1.0	3785.852	2350	2178.717	1300	1601.202	1050	764.007	550	1930.769	1050	1047.782	750

[a] DG and **SC power penetration in kW and kVAr respectively.

Table 8
Effect of DG units and shunt capacitors on real power loss and feeder current drawn by the network.

Load Level	Ploss_b (kW)	I(1,2)_b (p.u.)	Node Locations					
			Configuration 1		Configuration 2		Configuration 3	
			6		6, 3		6, 3, 28	
			Ploss_a (kW)	I(1,2)_a (p.u.)	Ploss_a (kW)	I(1,2)_a (p.u.)	Ploss_a (kW)	I(1,2)_a (p.u.)
0.4	29.7162	0.0178342	**13.5204**	**0.0003047**	**8.9069**	**0.0002723**	**6.9242**	**0.0002677**
0.5	47.0708	0.022412	21.2249	0.0001807	14.4223	0.0001466	10.5597	0.0001071
0.6	68.7376	0.0274159	30.7892	0.0000807	21.1225	0.0000323	15.8511	0.0000738
0.7	94.9114	0.0317253	42.0692	0.0001197	28.025	0.0003344	20.2933	0.000285
0.8	125.8031	0.0364658	55.0808	0.0002142	36.7599	0.0002006	26.6891	0.0001274
0.9	161.6418	0.0412658	69.1815	0.0002650	46.2651	0.0001186	35.3703	0.0000707
1.0	202.6771	0.0461282	**85.6386**	**0.0002162**	**57.6046**	**0.0000829**	**43.6947**	**0.0002168**

Table 9
Comparison of DG unit and shunt capacitor placement for drawing negligible power from the grid at load level 1.0.

	Proposed Method			*Method in Ref. [49]*			
DG unit locations	6	3	28	9	23		30
Size (kW)	764.0065	1930.7694	1047.7819	911	669		1423
SC locations	6	3	28	10		21	
Size (kVAr)	550	1050	750	1050		1200	
Power loss (kW)	**43.6947**			**80.8**			

Table 10
Effect of Case A and Case B on minimum voltage magnitude.

Load Level	Vminb	Case A Configurations			Case B Configurations		
		1 (6)	2 (6,3)	3 (6,3,28)	1 (6)	2 (6,3)	3 (6,3,28)
0.4	0.9669 (18)	**0.9954 (25)**	**0.9881 (18)**	**0.9867 (18)**	**0.9953 (25)**	**0.9879 (18)**	**0.9884 (18)**
0.5	0.9583 (18)	0.9942 (25)	0.9807 (18)	0.9846 (18)	0.9942 (25)	0.9818 (18)	0.9832 (18)
0.6	0.9495 (18)	0.9931 (25)	0.9845 (18)	0.9815 (18)	0.9931 (25)	0.9808 (18)	0.9813 (18)
0.7	0.9406 (18)	0.9919 (25)	0.9744 (18)	0.9777 (18)	0.9919 (25)	0.9757 (18)	0.9769 (18)
0.8	0.9316 (18)	0.9908 (25)	0.9717 (18)	0.9772 (18)	0.9908 (25)	0.9714 (18)	0.9754 (18)
0.9	0.9224 (18)	0.9895 (25)	0.9771 (18)	0.9691 (18)	0.9895 (25)	0.9704 (18)	0.9696 (18)
1.0	0.9131 (18)	**0.9883 (25)**	**0.9654 (18)**	**0.9641 (18)**	**0.9884 (25)**	**0.9658 (18)**	**0.9622 (18)**

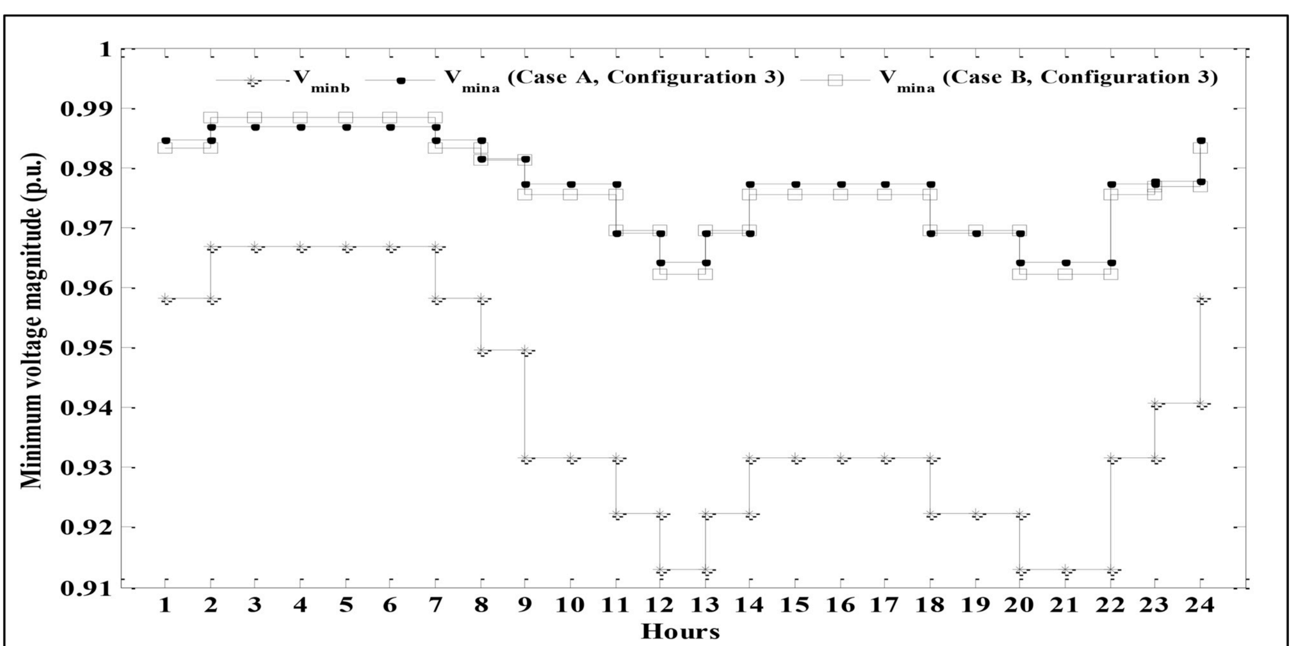

Fig. 6. Graphical representation of minimum voltage magnitude for 24 h average daily load schedule.

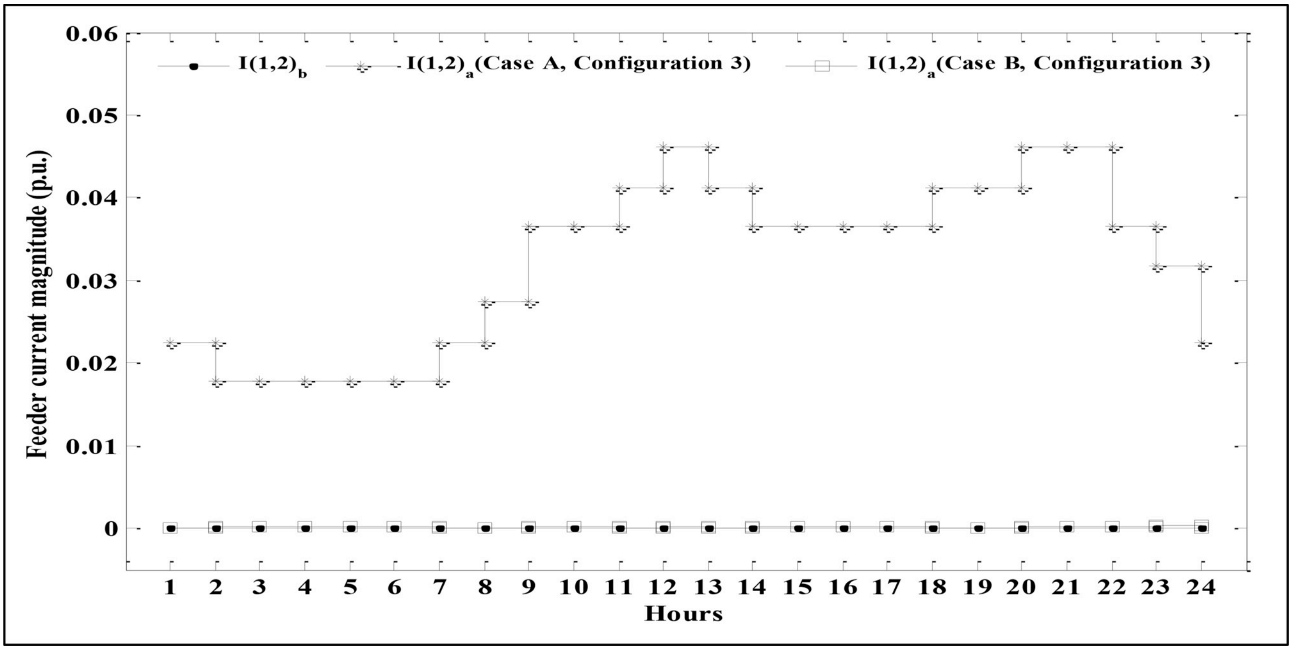

Fig. 7. Graphical representation of the substation feeder current for 24 h average daily load schedule.

Table 11
Numerical values of the variables used in cost analysis.

Variables	Numerical value
C	0.12 $\$/kWh$ [10]
N	18 years
r	10% $p.a.$
$DG_{\cos t}$	3000 $\$/kW$
$M_{\cos t}$	0.012 $\$/kWh$
D_1	6 $\$/kVAr$
D_2	1000 $\$/location$

and operation of the DG units. The energy savings after the placement of DG units and shunt capacitor banks is mathematically denoted by 'S' and defined as,

$$S = AS - I_{\cos t} - M_{\cos t} - SC_{p\cos t} - SC_{i\cos t} \quad (12)$$

where

$$AS = C\left\{\sum_{n=1}^{LL} (P^{before} - P^{after})T_n\right\} \quad (13)$$

$$I_{\cos t} = CRF * P_{DG\cos t} \quad (14)$$

$$M_{\cos t} = OM_{\cos t} * \sum_{n=1}^{LL} P_{dg} T_k \quad (15)$$

$$SC_{p\cos t} = D_1 * \sum_{n=1}^{LL} Q_{SC} \quad (16)$$

$$SC_{i\cos t} = D_2 * Q_{loc} \quad (17)$$

The capital recovery factor is defined by $CRF = \frac{r(1+r)^N}{(1+r)^N - 1}$. It is the amount to be paid in equal installments annually for 'N' years at an interest rate of r % p.a. The installation cost of the DG unit is defined as $P_{DG\cos t} = P_{dg}^{\max} * DG_{\cos t}$. The numerical values of the variables used in Eq. (12) – Eq. (17) are tabulated in Table 11.

The expresssion in Eq. (12) consists of five terms. The first term stands for the annual energy savings due to the reduction in substation power drawn by the network. The second and third terms represent the DG unit installation and maintenance expenses respectively. The fourth and the fifth terms express the capacitor purchase and the capacitor installation costs. The above mathematical representation is used to study the economic analysis of Cases A and B as considered in this paper. For Case A (DG units operating at lagging power factor), the capacitor terms (fourth and fifth) are dropped from Eq. (12). For Case B (DG units operating at unity power factor and shunt capacitors), the entire mathematical expression is used. The cost benefit analysis is explained with the help of a flowchart as shown in Fig. 8. The economic analysis is carried out for an entire year and the values are tabulated in Table 12.

The annualized cost savings are computed for three configurations (1, 2 and 3) as considered in this work. Tables 4–5, 7–8 are considered for the economic analysis. It can be seen that there has been considerable annualized savings in all the cases. Confiuration 3 is seen to be superior in terms of economic savings both in Case A as well as Case B. Depending on the availability and investment capability, either configuration of approach can be considered for utility long term benefits.

7. Conclusions

This paper presents the optimal placement and sizing of biomass based DG units and shunt capacitors in the distribution network considering negligible power being drawn by the network from the grid. An average daily load schedule has been modeled for the successful study of the above objective. Sensitivity analysis based on voltage stability index has been used for the placement of DG units and shunt capacitors. The sizing of the DG units and shunt capacitors has been obtained by optimizing a quadratic objective function using genetic algorithm. Two cases have been considered using DG units and shunt capacitor banks for the study of the aforesaid objective. Under each case, three configurations have been formed to analyze the technical and economic aspects of the problem. Cost economic benefits for all the configurations under each case have been evaluated. The proposed method has been compared with other existing methods in the literature and it has been

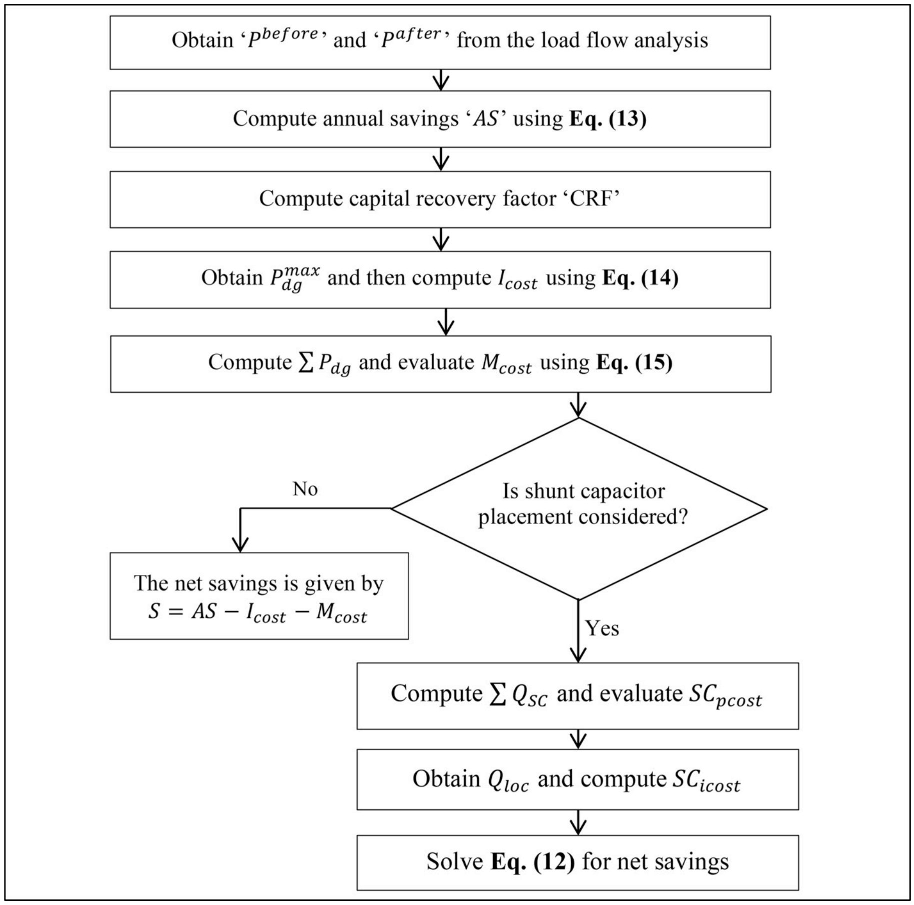

Fig. 8. Flowchart for cost analysis.

Table 12
Annualized cost savings.

	Case A Configurations			Case B Configurations		
	1	2	3	1	2	3
Annualized energy savings ($)	2874233.2	2874817.28	2875915.75	2869480.8	2870358.85	2871750
Annual DG investment cost ($)	1389823.7	911508.124	636720.394	1390164.7	800025.213	708978.5
Annual DG unit O&M Cost ($)	281045.95	280412.186	232610.686	280530.03	280739.228	278386.1
Capacitor Investment Cost ($)	–	–	–	69700.0	70100.0	71100.0
Annualized Net Savings ($)	**1203363.5**	**1682896.97**	**2006584.67**	**1129086.1**	**1719494.41**	**1813285.4**

found that the results demonstrate the effectiveness of the proposed methodology in drawing negligible power from the grid. The performance parameters of the network have been significantly improved in terms of voltage profile improvement, reduction of real power loss and reduction of substation feeder current drawn by the network. Of all the configurations studied, Configuration 3 in Cases A and B has proved to be better in terms of technical and economic aspects. Overall, it can be concluded that any set of approach under the proposed methodology can be considered by utilities for long term benefits depending on investment capability and the availability of resources.

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