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OPTIMAL ALLOCATION OF MULTIPLE DGS IN RDS USING PSO AND ITS IMPACT ON SYSTEM RELIABILITY

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Abstract. *This article presents the distributed generator (DG) integration in a radial distribution system (RDS). The DG penetration changes the single power source to multiple power sources and bidirectional load flow which enhances the system reliability and reduces system power losses. The particle swarm optimization and gravitational search algorithm are implemented for the optimal siting and sizing of one and three DG units in the RDS to examine its impact on system reliability and loss reduction. The types of DGs considered are Type I (injects real power) and Type IV (injects reactive and real power). The constant power is the chosen load model. The reliability indices taken for the analysis of system reliability are Average Energy Not Supplied, Total Energy Not Supplied and Average System Interruption Duration Index. The efficacy of the proposed method is validated on 33-bus in the presence of single and multiple DGs. The significant decrease in system power losses with the upgraded bus voltage profile, system reliability and remarkable annual loss saving is analyzed for Type IV DG over Type I DG. The results determined are compared to other meta-heuristic approaches as well as analytical techniques to demonstrate the superiority of the proposed methodology. The results are also statistically verified.*

Key words: *DG, siting and sizing, PSO, GSA, AENS, ASIDI, TENS, reliability, radial distribution system*

1. INTRODUCTION

The high rate of growing population, industrialization and global economic expansion motivates a massive investment in the reliable power supply. The component failure in the radial distribution system (RDS) is the primal cause of power interruption which reduces system reliability and produces a significant impact on distribution utilities and consumers. Hence, the need for a reliable power supply has been very important. Many corrective measures such as network reconfiguration have been tried out to restore the power supply until the replacement of the failed components using tie and sectionalizing switches. Due to the lack of such functionalities, the penetration of distributed generator (DG) in the RDS

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plays a vital role in providing reliable supply [1-2]. Based on the type of power delivering capability the DGs are classified as mentioned [3]

Type I (injects real power, power factor (PF)=1): Ex. Photovoltaic, battery, fuel cell
Type II (injects reactive power, PF=0): Ex. synchronous capacitor
Type III (injects real power, consumes reactive power, PF is leading): Ex. induction generator
Type IV (injects reactive and real power at lagging PF): Ex. synchronous generator, wind power

The optimal penetration of DG in RDS has many advantages like enhancement in bus voltage profile, system reliability and power loss reduction but it may adversely impact the system if not integrated optimally. The DG allocation methods are classified as analytical and meta-heuristic methods. The analytical technique uses mathematical expressions for the computation of the optimal solution. In [4], the authors have proposed an analytical expression to find DG size without evaluating cost benefits associated with it. Numerical methods such as mixed integer non-linear programming [5] and Kalman filter [6] have been utilized to integrate DG optimally in RDS. In [7], the authors have proposed a multi-objective index-based approach to find the optimum size and site of DG in RDS with consideration of voltage deviation at the critical node and tail-end nodes simultaneously. A power stability index is developed in [8] to optimally site the DG in RDS but considers Type I DG only. Many meta-heuristics approaches such as ant lion optimization algorithm [9] and non-dominated sorting genetic algorithm-II [10] have been utilized to solve DG installation issues. A new voltage stability index has been developed for optimal integration of various types of DGs using analytical and particle swarm optimization (PSO) approach to analyse system performance [11].

The comparison of two surveys conducted between the Canadian and United States utilities in regard to service utility data collection and its utilization is presented in [12] to show the service continuity statistics. Authors in [13] demonstrate the effect of location and numbers of DG units on the reliability indices of the RDS. The assessment of reliability indices is demonstrated in [14] under uncertainties but not for the multiple DGs. The relationship between DG penetration and power supply reliability of RDS has been analysed and presented in [15] but only for the small-scale system. A new methodology is described in [16] to estimate the DG impact on the reliability indices in the presence of system constraints. The penetration of multiple DG units in RDS may generate an adverse effect on system reliability due to excessive power injection as shown in [17]. The effect of installing different sizes of DG at different distances from the substation on the reliability indices is demonstrated in [18]. In [19], authors have demonstrated the effect of optimal penetration of multiple DGs on system power losses and reliability index in the existing RDS.

It has been observed from the previous work, that very few researchers had worked upon the impact of optimal installation of multiple DG units on reliability indicators to analyze the distribution system reliability. In this article, as a first step, the optimal allocation of multiple types of DG units using PSO and gravitational search algorithm (GSA) has been carried out in RDS considering various operational limits. Thereafter, the effect of DG placement not only on system power losses and bus voltage but also on reliability indicators, namely, Total Energy Not Supplied (TENS), Average Energy Not Supplied (AENS) and Average System Interruption Duration Index (ASIDI) is carried out. The types of DG taken for this research work are Type I and Type IV. The efficacy of the presented technique has been tested on IEEE 33-bus system. The load model selected for this study is constant power type. Based on the type of DG integration, two case studies are identified and presented. The main contributions of this article are mentioned below:

i. Two meta-heuristic techniques have been implemented for the simultaneous siting and sizing of one and three DG units in RDS and their results are compared.
ii. The impact of Type I and Type IV DG allocation on reliability indicators such as TENS, AENS and ASIDI has also been analysed in addition to system voltage profile and power losses.
iii. The percentage real power loss reduction (PLR) to penetration level (PL) ratio is determined to show the efficacy of the proposed method over other analytical and meta-heuristic methods.

The rest of the research article is arranged as follows: The mathematical modeling of load, line and DG is demonstrated in section 2. Section 3, Section 4 and Section 5 explains the development of problem formulation, system reliability indicators and the working of PSO and GSA, respectively. The solution methodology for multiple DG units installation using PSO approach is discussed in section 6. The result analysis has been discussed in Section 7. In Section 8, the conclusions of the paper are drawn.

2. Mathematical Modeling

2.1. Line and load model

System loads are considered to be concentrated at its nodes. Most of the system loads in RDS are voltage- and frequency-dependent [20]. For the analysis of static load, variation in voltage is taken into account as frequency deviation is insignificant [21]. In this article, the load is modeled as a constant complex power type. The one-line diagram (SLD) of a branch connected between *i-1th* and *ith* bus is demonstrated in Fig. 1. In short-line distribution model, the line-to-ground capacitance is very small and hence neglected [22].

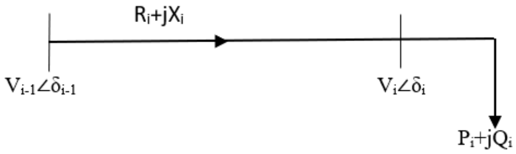

Fig. 1 Electrical equivalent of one branch

From Fig. 1, we get

$$\boldsymbol{P_i + jQ_i = V_i \angle \delta_i . I_i^*} \tag{1}$$

where V_i is receiving-end bus voltage and V_{i-1} is sending-end bus voltage. δ_i represents voltage angle at ith bus. Q_i and P_i represents reactive and active power load fed to bus i, respectively. Conjugating both sides of Eq. (1), we get

$$P_i - jQ_i = (V_i \angle \delta_i)^* . I_i \tag{2}$$

The receiving-end bus voltage is given as

$$V_i \angle \delta_i = V_{i-1} \angle \delta_{i-1} - (R_i + jX_i) I_i \tag{3}$$

where R_i and X_i represents the branch resistance and the branch reactance, respectively and δ_{i-1} shows the voltage angle at *i-1*th bus. From Eq. (2) and Eq. (3), the magnitude of receiving-end voltage is determined and given in Eq. (4)

$$V_i = \left[\left\{(R_iP_i + X_iQ_i - \tfrac{1}{2}V_{i-1}{}^2)^2 - (R_i{}^2 + X_i{}^2)(P_i^2 + Q_i^2)\right\}^{\frac{1}{2}} - (R_iP_i + X_iQ_i - \tfrac{1}{2}V_{i-1}^2)\right]^{\frac{1}{2}} \quad (4)$$

The branch RPL (P_{loss}) and branch reactive power loss (Q_{loss}) between bus *i-1* and bus *i* is expressed as

$$P_{loss}(i-1, i) = \frac{(P_i{}^2 + Q_i^2)}{|V_i|^2} . R_i \quad (5)$$

$$Q_{loss}(i-1, i) = \frac{(P_i{}^2 + Q_i^2)}{|V_i|^2} . X_i \quad (6)$$

The LF algorithm applied in the paper is backward-forward (b/f) sweep [23]. A tolerance of 10^{-4} p.u in bus voltage difference in two successive iterations at all the buses is considered as the stopping criteria.

2.2. DG Modeling

The DG resources of high rating can lead to situation wherein losses are more than the base case [4]. The DG resources of small size generally operate in constant power mode, that is, the generator bus is being modeled as a constant negative PQ load. However, the DG can be modeled wherein DG associated bus is considered as PV bus and the total reactive power penetrated by the DG is kept at a fixed voltage level. According to IEEE 1547 Standard [24], the utilities do not recommend the DG units to regulate bus voltages in order to avoid their conflict with the existing voltage control schemes [25]. In addition to this, as the amount of reactive power delivered by the generator depends upon the system configuration and cannot be stated in advance. Therefore, the DG is modeled as PQ load. The system performance in terms of voltage upgradation and loss minimization attained from 3rd Type of DG is worst among all other DG types of DG [26]. The change in the load demand at a bus is dependent upon the power injected by the DG. If a DG is placed at bus i, then the equivalent load at the same bus can be articulated as

$$P_i^{eq} = P_i - P_{DGi} \quad (7)$$

$$Q_i^{eq} = Q_i - Q_{DGi} \quad (8)$$

where, Q_{DGi} and P_{DGi} represents the reactive and real power penetrated by DG at bus i, respectively. The magnitude of reactive power injected at bus i for a given PF of Type IV DG is

$$Q_{DGi} = P_{DGi}.\tan\left(cos^{-1}((PF)_{DG})\right) \quad (9)$$

3. Problem Formulation

The objective of installing multiple DG units of multiple types in RDS is to upgrade bus voltage profile and system reliability with reduction of power losses. The PSO and GSA based technique has been implemented for the optimal installation of single and multiple DG considering Eq. (10) as the objective function

$$Objective\ function\ (OF) = \ Minimize\ \sum_{i=1}^{N_b-1} P_{loss}(i-1, i) \tag{10}$$

where N_b is the total buses of the system. The operational constraints are as follows:

a) Power balance principle:

$$P_G = P_D + P_{loss} \tag{11}$$
$$Q_G = Q_D + Q_{loss} \tag{12}$$

where Q_G and P_G represents the generated reactive and real power. Q_D is system reactive load demand and P_D is system real load demand.

b) Bus voltage limits:

$$0.95\ p.u \le V_i \le 1.05\ p.u \tag{13}$$

c) Branch ampacity constraints:

$$I_{branch} \le I_{thermal} \tag{14}$$

where, I_{branch} and $I_{thermal}$ represents the branch current and its thermal limit, respectively.

d) Constraints on DG power generation:

$$0 \le P_{DGi} \le \sum P_{Load} \tag{15}$$
$$0 \le Q_{DGi} \le \sum Q_{Load} \tag{16}$$
$$0 \le S_{DGi} \le \sum S_{Load} \tag{17}$$

where S_{DGi} represents the distributed apparent power generation and $\sum S_{Load}$, $\sum P_{Load}$ and $\sum Q_{Load}$ are the system's total load for apparent, real and reactive power, respectively.

e) Distribution substation capacity:

$$0 \le P_g^i \le P_{g(max)} \quad \text{i} \in \text{slack} \tag{18}$$

$$0 \le Q_g^i \le Q_{g(max)} \tag{19}$$

where $Q_{g(max)}$ is maximum reactive power generation and $P_{g(max)}$ is maximum real power generation, at slack bus.

4. SYSTEM RELIABILITY INDICATORS

Planning procedure uses reliability indicators for deciding new investments in new generation capacities. In this article, the effect of different DG units in the RDS is assessed by considering the following reliability indicators:

a) Total Energy Not Supplied
TENS is a measure of distribution system in adequacy and is estimated using Eq. (20)

$$TENS = \sum_{e=1}^{nl} \lambda_{a(e)} u_e \qquad \text{(MWh/yr)} \tag{20}$$

where, *nl* is the total load points count, $\lambda_{a(e)}$ is the unavailability of the load point e (kW) and u_e is the annual outage time in hours/year. The annual outage time is the summation of total load outages occurred due to branch failure and can be calculated as

$$u_e = \sum_{nl} \lambda_f r_e \quad (21)$$

where, r_e is the repair time (hours) or the total interruption time of the load and λ_f is the failure rate.

b) Average Energy Not Supplied
The AENS is estimated using Eq. (22)

$$AENS = \frac{\sum_{e=1}^{nl} \lambda_{a(e)} u_e}{\sum N_e} \quad (\text{MWh/customer} - \text{yr}) \quad (22)$$

where, N_e is the number of customers at e.

c) Average System Interruption Duration Index
The ASIDI calculates the average duration of the interrupted system load due to the occurrence of the outages. Mathematically, it can be given as Eq. (23)

$$ASIDI = \frac{\sum L_e r_e}{L_T} \quad (\text{hours or minutes}) \quad (23)$$

where, L_e is the load interrupted and L_T is the total connected load.

d) Customer Average Index Duration Index (CAIDI)
The CAIDI is the ratio of sum of customer interruption duration to the total number of the customer interruption and is given as Eq. (24)

$$CAIDI = \frac{\sum u_e . N_e}{\sum \lambda_f . N_e} (\text{hours/cust} - \text{interruption}) \quad (24)$$

e) System Average Interruption Frequency Index (SAIFI)
The SAIFI is the average number of interruptions per customer per unit time and is given in Eq. (25)

$$SAIFI = \frac{\sum \lambda_f . N_e}{\sum_{e=1}^{nl} N_e} \quad (\text{interruptions/customer-yr}) \quad (25)$$

The allocation of DG in RDS is a cost-effective solution to enhance system reliability as it is used in the distribution system as an alternative source for restoring power and may supply electric power to the loads that are failed due to faults. Hence, the integration of DG decreases the number of total customers not connected to the grid and outage time depending upon their output power which in turn reduces the numerator of all reliability indices mentioned in Eq. (20), (22), (23), (24) and (25) thereby enhancing distribution system reliability.

5. Optimization Algorithms

5.1. PSO algorithm

PSO is a stochastic approach wherein each particle changes its existing state in a multidimensional search space. If $V_{pd} = [v_{p1}, v_{p2} \dots .. v_{pn_d}]$ and $S_{pd} = [s_{p1}, s_{p2} \dots .. s_{pn_d}]$ demonstrate the velocity and the position of particle p, respectively; $d = 1,2, \dots n_d$ and $p = 1,2, \dots Ns$. Here, d signifies the current dimension, Ns signifies the swarm size and n_d is the dimension of the concerned problem.

$$v_{pd}^{k+1} = w_p v_{pd}^k + c_1 rand_1(pbest_{pd} - S_{pd}^k) + c_2 rand_2(gbest_{pd} - S_{pd}^k) \quad (26)$$

$$S_{pd}^{k+1} = S_{pd}^k + v_{pd}^{k+1} \quad (27)$$

where, S_{pd}^k and v_{pd}^k represents the current position and velocity of particle p at k^{th} iteration, respectively. c_2 and c_1 are the accelerating coefficients for 2^{nd} and 1^{st} particle, respectively. $rand_1(.)$ and $rand_2(.)$ are the random numbers distributed uniformly between 0 and 1. $pbest_{pd}$ and $gbest_{pd}$ is the particle's best position depending upon its personal experience and the global best position of the particle depending upon the experience of the overall swarm, respectively. The 1^{st} and 3^{rd} terms in Eq. (26) represents the inertia component and social component, respectively. The inertia weight of the p^{th} particle (w_p) decreases linearly with iterations and is mentioned as

$$w_p = w_{pmax} - \frac{(w_{pmax} - w_{pmin})}{k_{max}}.k \quad (28)$$

where, w_{pmin} and w_{pmax} are the min and the max value of w_p, respectively. k_{max} and k represents the maximum and current iteration number.

5.2. Gravitational search algorithm

GSA is a stochastic metaheuristic approach inspired by the law of gravitational and law of motion. The performance of the object is measured in terms of its mass. The laws results in global movement of all the considered objects towards the object having heavier mass. The agent's mass is calculated using Eq. (29)

$$M_g{}^k = \frac{m_g{}^k}{\sum_{h=1}^{Ng} m_h{}^k} \quad (29)$$

where,

$$m_g(k) = \frac{fit_g{}^k - fit_{worst}{}^k}{fit_{best}{}^k - fit_{worst}{}^k} \quad (30)$$

where, $fit_g{}^k$ and $M_g{}^k$ are the fitness value and the mass of agent g at k^{th} iteration. N_g represents the total number of agents. $fit_{best}{}^k$ and $fit_{worst}{}^k$ are the best and the worst fitness value among N_g at k^{th} iteration. The force acting between agent g and h as per the law of gravity is given in Eq. (31)

$$F_{ghd}^k = G^k.\frac{M_g{}^k.M_h{}^k}{D_{gh}{}^k + \mathcal{E}}.(S_{gd}^k - S_{hd}^k) \quad (31)$$

where, G^k is the gravitational constant at k^{th} iteration. $\mathcal{E}$ is a small constant which ensures the denominator is non-zero. $D_{gh}{}^k$ shows the Euclidian distance present between the agent g and h. The acceleration of agent g as per the law of gravity is given in Eq. (32)

$$a_{gd}^k = \frac{F_{gd}^k}{M_g{}^k} \quad (32)$$

where, F_{gd}^k is the force acting on agent g at iteration k in d dimension. The updated velocity and position of agent g is calculated as

$$v_{gd}^{k+1} = rand.v_{gd}^{k} + a_{gd}^{k} \tag{33}$$

$$S_{gd}^{k+1} = S_{gd}^{k} + v_{gd}^{k+1} \tag{34}$$

The value of G^k is set using Eq. (35)

$$G^k = G_o.e^{-\alpha\frac{k}{K}} \tag{35}$$

where, G_o is the initial value of the gravitational constant. K is the total number of iterations and reduces linearly to 1.

The sequence of steps the GSA follows are Identification of search space, random initialization of GSA parameters, fitness function evaluation, updation of GSA parameters, determination of force using Eq. (31), acceleration using Eq. (32) and velocity using Eq. (33) followed by updating agent's position using Eq. (34) till the stopping criteria is met.

6. Solution Methodology for Optimal Multiple DGs Allocation and Reliability Assessment Using PSO

The PSO-based method to allocate multiple DGs optimally in RDS for mitigating system power losses and the reliability indicators takes the following steps

- Step I: Solve the b/f LF problem for the base case to determine magnitude of system bus voltage and its power losses as mentioned in section 2.1.
- Step II: Calculate reliability indicators: TENS, AENS, ASIDI, CAIDI and SAIFI.
- Step III: Select PSO parameters (swarm size, acceleration coefficients and weight) to minimize the OF value.
- Step IV: Set iteration counter k as 0
- Step V: The values of the DG location and size are generated (between zero and sum of system loads (continuous)) with random velocities and positions on the dimension (locations & sizes of Type I and Type IV DG) as pbest.
- Step VI: Repeat the LF algorithm for every particle after placing DG randomly. If all constraints are within limits then compute OF for the randomly initialized particles. Else, reject the infeasible solution.
- Step VII: The DG site and size providing the lowest OF value is considered as gbest and its corresponding position is nominated as the particle best position.
- Step VIII: The value of particle's velocity, particle's position and its weight are updated using Eq. (26), Eq. (27) and Eq. (28), respectively.
- Step IX: If k_{max} is achieved, jump to Step X. Else, increment k and repeat steps IV through IX. A new pbest and gbest is generated and stored if the newly obtained values is found to be superior than the previous values.
- Step X: The best position signifies the optimal sites and sizes of multiple DGs and its corresponding OF value represents the minimum total RPL.
- Step XI: Calculate the value of TENS, AENS, ASIDI, CAIDI and SAIFI after optimal penetration of single and multiple DGs of the corresponding type with the values calculated in step II.

7. Numerical Results and Discussion

This paper demonstrates the effect of optimal installation of different DG units in RDS using PSO and GSA to mitigate system power losses and upgrade system reliability. The total capacity of the simultaneously placed multiple DGs is not to supersede the total system load. The total system data for 33-bus has been taken from [27]. The IEEE 33-bus system has a power demand of 3.715+j2.3 MVA and three laterals. The base kV and MVA taken for the test system are 12.66 and 100, respectively. The data taken for calculating reliability indicators are mentioned in the appendix section (Table 9 and Table 10). The total number of interruptions and customer with at least one interruption is considered as 10 and 4012, respectively. The failure rate of the system is assumed to be 0.5 f/yr. The PSO and GSA are tested on standard 33-bus RDS to verify its robustness. The PSO algorithm analyses the impact of single and multiple DGs placement, whereas, the GSA analyses the impact of single DG placement on system's reliability. The maximum iteration count and swarm size chosen for the PSO is 100 and 20, respectively. The values of PSO control variables c_1 , c_2 , w_{pmin} and w_{pmax} selected for the fast convergence are 2, 2, 0.4 and 0.9, respectively as in [28]. In GSA, the values of G_o and α is taken as 100 and 20, respectively as in [29]. The population size, K and dimension selected for the GSA technique is 33, 20 and 1, respectively. The proposed technique is implemented to calculate bus voltages, total system power losses, annual cost of energy loss (ACEL), annual savings and reliability indicators. The value of ACEL [30] is calculated using (36)

$$\boldsymbol{ACEL} = \left(\sum_{i=2}^{N_b} \boldsymbol{P_{loss}}\,(\boldsymbol{i-1}, \boldsymbol{i})\,\boldsymbol{T} * \boldsymbol{E}\right)\$ \tag{36}$$

where T and E are annual time duration (8760 hours) and energy cost (0.06 $/kWh), respectively. The comparative analysis of the obtained results has been carried out at the same base voltage and load model. The methodology to integrate multiple DGs in the test system is implemented in MATLAB.

The results of the 33-bus RDS before and after penetration of one and three DGs using PSO approach are compared and tabulated in Table 1. The total system real and reactive power loss in the absence of any type of DG is 210.07 kW and 142.43 kVAr, respectively. The value of TENS, AENS and ASIDI is also calculated for the uncompensated system and found out to be 8.0475 MWh/yr, 0.0004969 MWh/cust-yr and 0.2794 hours, respectively. The following case studies based on the type of DG penetration are as follows:

Table 1 Results of Type I DG installation in 33-bus RDS using PSO approach

	Base case	With DG	
		1 DG	3 DGs
		PSO	
Optimal DG size in kW (optimal bus)	-	2605(6)	1067.5(24), 779.7(14), 1091.8(30)
Minimum bus voltage (V_{min}) p.u @ bus (Improved voltage in %)	0.9042 @ 18	0.9436 @ 18 (4.35%)	0.9729 @ 33 (7.59%)
RPL (kW)	210.07	110.00	71.00
RPLR (kW) (% reduction in RPLR)	-	100.07 (47.63%)	139.07 (66.20%)
Reactive power loss (kVAr)	142.43	80.82	-
ACEL ($)	110413	57816.00	37317.6
Annual energy loss Savings ($)	-	52597.00	73095.4

Table 2 Impact of Type I DG installation on reliability indicators for 33-bus RDS

		TENS (MWh/yr)	AENS (MWh/cust-yr)	ASIDI (hours)
No DG		8.0475	4.9691e-04	0.2794
One DG	PSO	2.2230	1.3727e-04	0.0452
	GSA	1.8936	1.1693e-04	0.0461
Three DGs		1.5682	9.6834e-05	0.0541

7.1. Type I DG penetration

The optimal position of single DG placement is found out to be bus 6 after applying PSO technique with DG size of 2605 kW, whereas, for simultaneous positioning of multiple DGs, the buses 24, 14 and 30 are obtained with a DG capacity of 1067.5 kW, 779.7 kW and 1091.8 kW, respectively (From Table 1). The CPU time for the computation of LF in a 33-bus system considering Type I DG obtained from the PSO approach is 1.15 seconds and found out to give faster convergence as compare to other approaches viz. 4.2651 seconds [8] and 6.9255 seconds [31]. The optimal location and size of single Type I DG in 33-bus RDS using GSA is bus 6 and 2000 kW, respectively. The effect of penetration of single and multiple DGs on TENS, AENS and ASIDI are also analysed and mentioned in Table 2. The reduction in the value of reliability indicators after penetrating DGs in RDS demonstrates the improvement in system reliability.

7.1.1. Effect of Type I DG on system power losses

The optimal installation of a single DG minimizes the RPL by 47.63%, whereas, in the case of 3 DGs, the value of RPL reduces by 66.20% as illustrated in Table 1. This in turn releases the real power demand of 100.07 kW and 139.07 kW after penetration of single and multiple DGs, respectively, at unity power factor.

7.1.2. Effect of Type I DG on voltage profile

The minimum bus voltage of 0.9042 p.u without DG was attained at bus 18 which got enhanced to 0.9436 p.u at bus 18 and 0.9729 p.u at bus 33 for single and multiple DGs placement with a percentage voltage enhancement of 4.35% and 7.59%, respectively. The proposed methodology meets all the constraints except small voltage violation (lower limit) in case of single Type I DG i.e. 5.64% instead of 5% in the case of single DG placement (From Table 1). The impact of installing one and three DG on the convergence of bus voltage magnitude for 33-bus RDS is presented in Fig. 2 which displays that the multiple DG has better bus voltage profile than single DG placement.

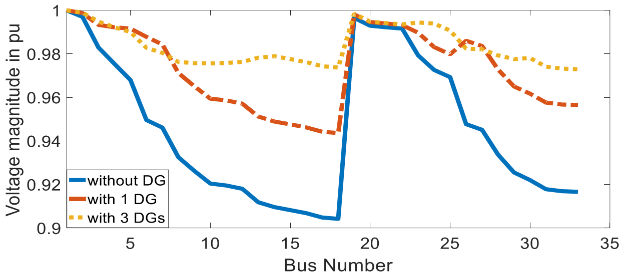

Fig. 2 Bus voltage profile without and with one and three Type I DGs

7.1.3. Effect of Type I DG on reliability indicators

The impact of single DG allocation on reliability indices in 33-bus RDS is carried out using PSO and GSA and the values are tabulated in Table 2. After locating single DG in the system, the values of TENS, AENS and ASIDI decreases with a percentage reduction of 72.37%, 72.42% and 83.82%, respectively for PSO, whereas, it is 76.47%, 76.46% and 83.50%, respectively for GSA, w.r.t the base case. The value of TENS, AENS and ASIDI becomes 1.5682 MWh/yr, 0.0000968 MWh/cust-yr and 0.0541 hours after the installation of three DGs, respectively (From Table 2). The percentage improvement in reliability indices with the penetration of single and multiple Type I DGs is illustrated in Fig. 3 and clearly infers that the percentage reduction in reliability indices is more with the installation of three DGs for TENS and AENS as compared to one DG. Hence, the injection of real power in the system enhances the system reliability, but excessive real power injection may create an adverse effect on ASIDI.

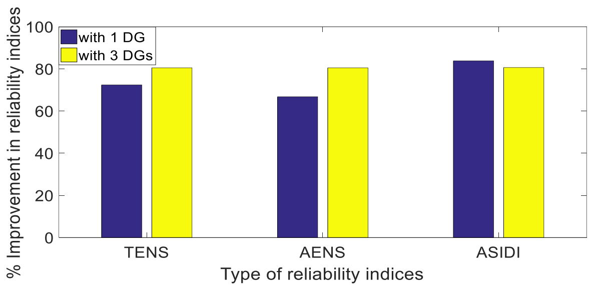

Fig. 3 Percentage improvement in reliability indices with single and multiple DGs

7.1.4. Effect of Type I DG on the cost of annual energy loss

The cost of annual energy loss obtained for the base case is $110413.00 which is reduced to $57816.00 and $37317.6 with the installation of one and three DGs, respectively. The annual energy loss saving after single and multiple DG placement is $52597.00 and $73095.4, respectively (From Table 1).

7.1.5. Result Comparison

The test results obtained without and with single and multiple DGs placement using PSO and GSA are compared to the already existing results and tabulated in Table 3. Due to varying nature of DG size and real power loss reduction (RPLR), a ratio of PLR to PL is introduced. The larger ratio indicates the dominance of the method employed to integrate DG optimally. PLR is the ratio of RPLR considering DG to RPL with no DG. PL is the ratio of real power penetrated by DG to the real power load. The ratio obtained from PSO and GSA in the presence of single and multiple DGs is determined to be either equal or superior to the previously published results. It is obvious from the results that, in the presence of three DGs the reduction in power loss (66.20%) is maximum. The ACEL with the penetration of three DGs is significantly less as compared to a single DG.

Table 3 Comparison of results for multiple Type I DGs in 33-bus RDS

		Installed DG size in kW (optimal bus)	Total DG capacity (MW)	RPL (kW)	PLR	Ratio of PLR to PL	ACEL ($)
No DG		-	-	210.07	-	-	110413.00
1 DG	Proposed method PSO	2605(6)	2605	110.00	47.63	0.68	57816.00
	Proposed method GSA	2000(6)	2000	114.60	45.45	0.84	60233.76
	IA [32]	2600(6)	2600	111.10	47.39	0.67	58394.16
	Grid search algorithm [33]	2600(6)	2600	111.00	47.39	0.67	58341.60
	PSO [34]	3150(6)	3150	115.29	45.36	0.53	60596.42
	KHA [35]	2590(6)	2590	111.02	47.38	0.53	58352.11
3 DGs	Proposed method	1067.5(24), 779.7(14), 1091.8(30)	2939	71.00	66.20	0.84	37317.60
	PSO-CFA [36]	1049.1(10),878.6(25),804.9(33)	2732.6	76.00	62.48	0.84	39945.60
	ShBAT [37]	1190.0(30), 849.0(25), 790.0(13)	2829	72.12	64.34	0.83	37906.27
	ACO-ABC [38]	754.7(14),1099.9(24),1071.4(30)	2926	71.40	64.77	0.81	37527.84
	ABC [31]	1756.9(6), 575.7(15), 782.6(25)	3115.2	79.20	61.15	0.73	41627.52
	GA [39]	1500(11),422.8(29),1071.4(30)	2994.2	106.3	49.61	0.59	55871.28
	MOCSOS [40]	1187.9(13),1197.1(24),1300.2(31)	3685.2	89.40	57.67	0.58	46988.64
	MOTA [41]	980(7),960(14),1340(30)	3280	96.30	54.36	0.56	50615.28
	GA/PSO [39]	925(11),863(16),1200(32)	2988	124.0	41.22	0.51	65174.40

7.2. Type IV DG allocation

For PSO approach, the optimal position after applying proposed methodology to locate a single Type IV DG is bus 6 with DG size of 3150 kVA, whereas, for the positioning of multiple DGs, the buses 24, 30 and 14 are determined with a DG capacity of 859.2 kVA, 1031.6 kVA and 605.3 kVA, respectively, as mentioned in Table 4. The optimal bus obtained using GSA to locate single Type IV DG is 6 with a DG capacity of 2828.42 kVA. The effect of penetration of single and multiple DGs on each reliability indicator using PSO and GSA is provided in Table 5.

Table 4 Results of Type IV DG installation in 33-bus RDS using PSO

	Base case	With DG	
		1 DG	3 DG
Optimal DG Size in kVA (optimal bus)	-	3150 (6)	859.2 (24), 1031.6 (30), 605.3 (14)
V_{min} in p.u @ bus (Improved voltage in %)	0.9042@18	0.9602@18 (6.19%)	0.9953@33 (10.07%)
RPL (kW)	210.07	64.00	17.00
RPLR (kW) (% reduction in RPLR)	-	146.07 (69.53%)	193.07 (91.90%)
ACEL ($)	110413	33638.40	8935.20
Annual energy loss Savings ($)	-	76774.60	101477.80

Table 5 Impact of Type IV DG installation on reliability indicators

		TENS (MWh/yr)	AENS (MWh/cust-yr)	ASIDI (hours)
No DG		8.0475	4.9691e-04	0.2794
One DG	PSO	1.7033	1.0518e-04	0.045287
	GSA	1.5702	9.6956e-05	0.045513
Three DGs		1.1429	7.0571e-05	0.054032

7.2.1. Effect of Type IV DG on system power losses

After optimal penetration of one and three DGs in RDS, the losses reduced to 64 kW and 17 kW with a reduction of 69.53% and 91.90%, respectively, as illustrated in Table 1 at 0.82 PF [28]. The reactive loss obtained without DG is 142.43 kVAr. The power loss reduction attained with the installation of single and multiple Type I and IV DGs is demonstrated in Fig. 4 which concludes that the allocation of multiple Type IV DGs gives the highest reduction in system RPL amongst all.

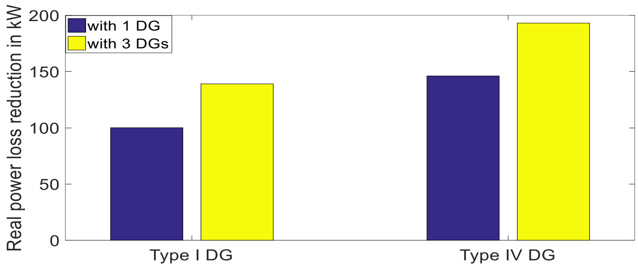

Fig. 4 RPLR with single and multiple Type I & Type IV DG penetration

The ACEL after penetration of single and multiple Type IV DGs is $33638.40 and $8935.20 which results in the annual energy loss savings of $76774.60 and $101477.80, respectively (From Table 4).

7.2.2. Effect of Type IV DG on system voltage profile

The installation of a single DG in 33-bus system improves the magnitude of bus voltage at bus 18 from 0.9042 pu to 0.9602 pu at bus 18 resulting in percentage voltage improvement of 6.19%. In the presence of multiple DGs the system voltage at bus 18 enhances from 0.9042 pu to 0.9953 p.u at bus 33 resulting in percentage bus voltage improvement of 10.07%. The impact of installing single and multiple Type IV DGs on the convergence of voltage magnitude at each bus is presented in Fig. 5, which demonstrates that the bus voltage profile with multiple DG units is over-represented as compare to one DG placement.

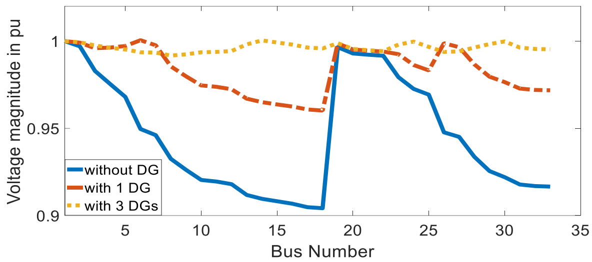

Fig. 5 Comparison of bus voltages in presence of single and multiple Type IV DGs penetrations

P+jQ indicates the system's nominal loading. The impact of system loading on the magnitude of bus voltage with optimally placed DG (at bus 6) is evaluated by incrementing load gradually at all the buses as mentioned in Table 6 [11]. At critical loading, the voltage at bus 6 got reduced from 0.9496 p.u. to 0.7594 p.u. The value of critical loading factor obtained for 33-bus system is 3.405 after which there will be a voltage collapse. The subsequent incorporation of DG enhances the voltage magnitude at all the buses and hence provides stable operation with enhanced system capacity.

Table 6 Impact of system loading & Type IV DG on voltage for 33-bus [11]

System load	RPL (kW)	Reactive power loss (kVAr)	Voltage in p.u @ bus 6	DG size (kVA) @ bus 6
P+jQ	210.0704	142.4372	0.9496	0
2(P+jQ)	1016.33	691.98	0.8894	0
3(P+jQ)	3094.5	2122.31	0.8078	0
3.405(P+jQ)	4905.40	3382.42	0.7594	0
3.41(P+jQ)	NC	NC	NC	0
3.41(P+jQ)	2463.5	1755.3	0.8545	1000
3.41(P+jQ)	1412.3	1062.1	0.9263	2000

NC: No Convergence

7.2.3. Effect of Type IV DG on reliability indicators

The value of TENS, AENS and ASIDI obtained from PSO method after placement of a single Type IV DG is 1.7033 MWh/yr, 0.00010518 MWh/cust-yr and 0.045287 hours which becomes 1.1429 MWh/yr, 0.00007057 MWh/cust-yr and 0.0540 hours in the presence of three DGs, respectively (From Table 5). The drop in the reliability indicators shows system reliability improvement. The % improvement in the value of TENS and AENS incorporating single Type IV DG using GSA is 7.81% and 7.82%, respectively. The impact of single and multiple Type IV DGs on the percentage reduction in reliability indices is illustrated in Fig. 6. The percentage reduction in TENS and AENS is higher due to the installation of three DGs as compared to one DG, except ASIDI. The results demonstrate that the value of TENS and AENS decreases with higher DG penetration, whereas, the value of ASIDI increases due to excessive real power penetration.

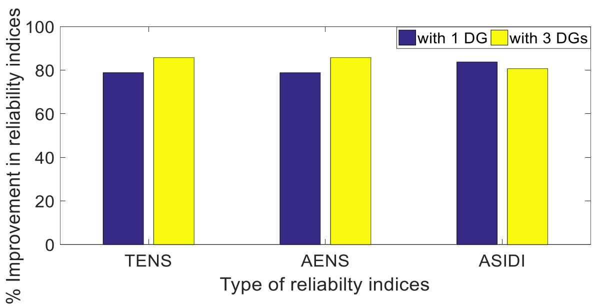

Fig. 6 Percentage improvement in reliability indices with different number of Type IV DGs

In addition to this, the impact of optimal allocation of three DG (Type IV) units on CAIDI and SAIFI have also been analysed. For an uncompensated system the values of CAIDI and SAIFI is 0.62466 (hours/$\text{cust} - \text{interruption}$) and 0.72337 (interruptions/customer-yr) which got reduced to 0.62305 (hours/$\text{cust} - \text{interruption}$) and 0.72028 (interruptions/customer-yr), respectively after integration of Type IV DG units. These indices are difficult to compare from one utility to another and from one location to another because of the differences in the calculation of the number of customers connected. Some utilities determine their number of customers based on the total number of meters connected and some based on customer postal addresses and do not considers the weather conditions and planned outages for reliability calculation.

7.2.4. Comparison of results

The comparative analysis without and with the integration of single and multiple Type IV DGs has been carried out and tabulated in Table 7. The value of PLR and ratio of PLR to PL attained from the proposed method is found out to be the highest among all reported results for one and three DGs. The ratio obtained from GSA for single DG placement is found out to be superior than PSO. The presented methodology leads to a superior solution causing minimum annual energy loss in most cases. It is obvious that the V_{min} and reduction in system RPL attained with multiple DGs of Type IV is superior to single DG.

Table 7 Comparison of results for multiple Type IV DGs in 33-bus RDS

		Installed DG size in kVA (optimal bus)	Total DG capacity (kVA)	RPL (kW)	PLR	Ratio of PLR to PL	ACEL ($)
No DG		-	-	210.07	-	-	110412.8
1 DG	Proposed method PSO	3150(6)	3150	64.00	69.53	0.813	33638.40
	Proposed method GSA	2828.42(6)	2828.42	64.55	69.27	0.91	33927.48
	IA [32]	3107(6)	3107	67.90	67.85	0.809	35688.24
	MINLP [42]	3105(6)	3105	67.85	67.84	NR	35661.96
	GAMS [43]	3078(6)	3078	67.80	67.80	NR	35635.68
3 DGs	Proposed method	859.2(24),1031.6(30),605.3(14)	2496.1	17.00	91.90	1.36	8935.20
	TM [41]	705.2(16),705.2(27),1410.4(30)	2820.8	27.4	87.01	1.14	14401.44
	DGSI [44]	1208(13), 1208(29),152(31)	2568	49.8	76.22	1.09	26174.88
	LSFSA [45]	1382.9(6),551.7(18),1062.9(30)	2997.5	26.7	86.82	1.08	14033.52
	MOTA [41]	880(14),920(25),1560(30)	3360	15.7	92.55	1.00	8251.92
	MOCSOS [40]	926.1(13),1257(24),1481.2(30)	3664.3	15.1	92.83	0.93	7936.56

NR: Not reported

7.3. Statistical analysis of RPL

From Table 8, the value of coefficient of variation (CV) of RPL in the presence of single Type IV DG is minimum as compared to the other types of DGs. This demonstrates that the Type IV DG is capable in reducing the variation in system power losses in distribution feeders around its mean value much more effectively than the Type I DG and hence give better security against overheating of the distribution feeders.

Table 8 Statistical results for 33-bus with and without Type IV DG using PSO technique

DG Type	P_{loss} (kW)				
	Min	Max	Mean	Std	CV
No DG	0.013	51.896	6.570	11.536	1.756
Type I	0.012	15.457	3.425	4.099	1.196
Type IV	0.010	9.9412	1.993	2.367	1.187

8. Conclusion

This article presents a comprehensive strategy to optimally allocate multiple Type I and Type IV DGs in the existing RDS to reduce RPL, reliability indicators (TENS, AENS and ASIDI) and improve bus voltage profile. The optimal integration of DG units is carried out using PSO and GSA based approach which is capable to determine optimal solution with or without few assumptions even in a large search space. The comparative analysis on 33-bus system has been carried out for single and multiple DGs placement in the RDS. The analysis clearly illustrates that the system performance in terms of reduction in system power losses, enhancement in TENS, AENS, bus voltage profile and AELS is superior for multiple DGs placement when compared to single DG. The results also demonstrated that the penetration of DG resources in RDS using PSO and GSA method improves TENS and AENS, but excessive power injection may create an adverse effect on ASIDI. An approach like GSA founds to provide better results than PSO for TENS and AENS improvement in case of single DG. The optimal integration of multiple Type IV DG is found to have many positive impacts on system performance.

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APPENDIX

Table 9 Number of customers at each bus

Bus number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Total no. of customers	500	600	750	250	425	220	500	640	800	600	730	640	550	920	120
Bus number	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**
Total no. of customers	60	340	410	230	260	550	650	290	270	700	250	420	720	850	760
Bus number	**31**	**32**	**33**												
Total no. of customers	180	350	660												

Table 10 Customer interruption details at five load points

Load points	Unavailable buses	Off time (min)
1	5, 21, 24, 6, 3	28
2	12, 7, 21, 4, 21	40
3	6, 3, 13, 16, 24	14
4	16, 9, 14, 10, 7	60
5	8, 19, 6, 1, 12	35