RESEARCH ARTICLE

The Optimal Integration of Multiple DGs under Different Load Models using Artificial Bee Colony-Hill Climbing Algorithm

Lokesh Mallaiah[1,*], Ananth D. Kulkarni[2], Babu Rajendra Prasad[3] and Ananthapadmanabha Tammaiah[4]

[1]*Department of Electrical and Electronics Engineering, NIE Institute of Technology, Mysuru, India*
[2]*Department of Electrical Engineering, The National Institute of Engineering, Mysuru, India*
[3]*Department of Electrical and Electronics Engineering, VVCE, Mysuru, India*
[4]*School of Engineering, Mysore University, Mysuru, India*

([*]**Corresponding author's e-mail: lokesh@nieit.ac.in**)

Abstract

With the continual advances in technologies, there is a significantly increased demand for electricity leads to a drastic increase in usage and penetration of DGs into the distribution network. The incorrect addition of DGs into the distribution system resulting in declining stability, power losses, voltage profile, reliability, and power quality of the system. Therefore, the optimal planning of DGs (OPDG) has always been under constant investigation and development for the maximum beneficiary. The proposed framework presents a novel meta-heuristic hybrid optimization technique called Artificial Bee Colony-Hill Climbing (ABC-HC) to find the best siting and sizing of multiple DGs using a weighted multi-objective function which includes real and reactive power loss index and voltage deviation index. The results clearly indicate the significant reduction in losses and voltage deviation achieved by integration of single and multiple DGs. The research work is also extended to assess the voltage harmonics of the system before and after the placement of DGs. The effectiveness of the proposed ABC-HC algorithm has been demonstrated on the standard IEEE-33 bus RDS under different voltage dependent load models using MATLAB 2017a.

Keywords: Optimization technique, Radial distribution system, Distributed generation, Artificial bee colony, Hill climbing

Introduction

A complex conventional power system is serving the society in supplying the required power to the consumers over the past decade. The advancement in technology taking place to make the system more reliable and effective for supple flow of power and also an uninterruptable power source to the demand side. On the other hand, in India, the present transmission and distribution system losses is around 20 % of the generation. An alternative technology, such as the restructuring of the system and inclusion of DGs are being explored to weaken the above-said problems. The distributed generators are small generators of different technologies comprising conventional and/or non-conventional type which is installed and commissioned near the load side. The low voltage and high level of current in distribution system leads to more power loss. Hence to minimize the losses and to avail the maximum benefit of DGs, it has been integrating into the distribution system. Therefore, the DG technologies and integration of it with distribution network gaining popularity as an advanced solution for the power system problems. Unfortunately, the bad selection of size and site has negative impacts on the system which makes the system performance worst. Hence, the optimal planning of DGs is a very active and burgeoning area of research.

Research in this field is dominated by providing optimal planning of DGs using single as well as multi-objective function. Most of the research in OPDG is aimed to reduce both the active and reactive power loss, voltage profile improvement, and operating cost minimization. A systematic review reveals different approaches of problem-solving techniques consisting of both analytical and metaheuristic

methods. The analytical method is a mathematical based approach which is more complex and time-consuming. To overcome the shortcoming, meta-heuristic method attracts more researchers to address the issue. The literature was also reviewed that the simple techniques which are derived to minimize the complexity of the problem by formulating indices like Power loss index (PLI), Voltage deviation Index (VDI), voltage Stability index (VSI), and Loss sensitivity index (LSI).

Over the years, metaheuristic approach has been used extensively for optimal planning of DGs. Fazlina [1] used multi-objective function consisting of loss reduction and THD reduction to avail maximum benefit through evolutionary programming approach based OPDG. El-Zonkoly [2] examined the particle swarm optimization (PSO) technique to optimize the DG integration problem based on multi-objective index. The analysis was carried out by finding the sensitive bus towards voltage collapse and this method is evaluated under different load condition. A random search-based hybrid algorithm Chaotic Sine Cosine Algorithm (CSCA) is adopted for optimal planning of multiple DGs using single and multiple objective function [3]. In [4] the optimization problem is solved by employing point estimate method using novel combined Ant Colony optimization and Artificial Bee colony (ACOABC). The DG and DSTATCOM are optimally planned with Bacterial Foraging optimization Algorithm (BFOA) with multiple objective function [5].

Moradi [6] proposed a new combinational method of Genetic algorithm (GA) and PSO to reduce the system power loss and also to enhance voltage stability. The optimal planning of multiple DGs with multi-objective function has been approached by using gravitational search algorithm and general algebraic modelling system (GSA-GAMS), Fireworks algorithm and adaptive shuffled frogs leaping algorithm (ASFLA), Backtracking search optimization algorithm (BSOA), Intelligent Water drop algorithm (IWD), Invasive Weed Optimization (IWO), Salp swarm algorithm (SSA), Artificial Bee colony and Cuckoo Search (ABC-CS), Flower Pollination Algorithm (FWA), Lightning Search Algorithm (LSA), Strength Pareto Evolutionary Algorithm (SPEA2) [7-16]. The algorithms were tested on IEEE 33 and 69 bus RDS [2-16]. Rather fewer attempts have been undertaken for addressing the OPDG problem on distribution system in voltage-dependent load environment. Hence The purpose of this work is to present a hybrid ABC-HC algorithm to optimize the location and sizing of multiple DGs based on multi-objective function. The proposed technique is extended to evaluated for different voltage dependent load models. The impacts of integration of DGs on RDS power quality is of high interest and therefore the propose work also focuses on to evaluate the impact of DGs on voltage THD in all considered load types using harmonic load flow analysis. To demonstrate the potential of the proposed ABC-HC algorithm, the analysis is carried out on IEEE-33 bus RDS using MATLAB 2017a and the key findings of the work are compared with state-of-the-art algorithm illustrated in the literature.

The rest of the manuscript is organized as follows: The multi-objective optimization problem formulation is described in section 2. In section 3, the implementation of harmonic flow analysis is discussed. Section 4 presents how the proposed algorithm is implemented to obtain OPDG. The results and comparison of the proposed algorithm is presented in sections 5 and 6 concludes the findings.

Problem formulation and load types
To make the calculation simple and to reduce the computational time the indices are derived. In the proposed approach, the popular 3 indices are combined to frame a multi-objective index-based problem statement. The value of all individual indices is taken as unity for the base case and the optimal planning has been carried out to reduce these indices. The Newton Raphson Load Flow (NRLF) analysis is employed to find the indices. The indices are mentioned below:

Active power loss index (APLI)
The value of APLI indicates the effectiveness of adding DG into the network in reducing active power loss. The maximum benefit of DG in reducing the losses is indicted by low value of the indices and the index is represented in Eq. (1). The I^2R losses of RDS is calculated by using Eq. (2).

$$APLI = \frac{P_L^{DG}}{P_L^B} \tag{1}$$

$$P_L = \sum_{i=1}^{Nb} I_{(i,i+1)}^2 R_{(i,i+1)} \tag{2}$$

Where, P_L^{DG} and P_L^B are the active power loss with and without DG respectively.

Reactive power loss index (RPLI)

The RPLI defines how optimally DG planning has been done in minimizing reactive power losses. Lesser the value of RPLI signifies higher the percentage of reactive power loss reduction and it is represented in Eq. (3). The reactive power line losses of RDS are calculated using Eq. (4).

$$RPLI = \frac{Q_L^{DG}}{Q_L^B} \tag{3}$$

$$Q_L = \sum_{i=1}^{Nb} I_{(i,i+1)}^2 X_{(i,i+1)} \tag{4}$$

Where, Q_L^{DG} and Q_L^B are the reactive power loss with and without DG.

Total voltage deviation index (TVDI)

The TVDI index is derived to estimate the amount of deviation in the node voltage of the system thereby it represents the enhancement of voltage profile after placing DGs. In this index, only if the voltage is not in the acceptable limit i.e. from 0.95 to 1.05 pu then only it will be considered as a voltage deviation or else the voltage deviation index is taken as 0 and is represented in Eqs. (5) - (6):

$$TVDI = \sum_{i=1}^{n} VDI \tag{5}$$

$$VDI = \begin{cases} \text{If } 0.95 \leq V_{DG_i} \leq 1.05, & \text{then } VDI = 0 \\ Else, & \text{then } VDI = \sum_{i=1}^{n} \frac{V_{ref} - V_{DG_i}}{V_{ref}} \end{cases} \tag{6}$$

where $V_{ref} = 1$, V_{DGi} is voltage at bus i after placement of DG, n is the number of bus.

Multi-objective function

The 3 indices are combined together to formulate a multi-objective function and different weightage has given for the OPDG to minimize real and reactive line losses and voltage deviation. The fitness function is given in Eq. (7):

$$F_{Min} = a * APLI + b * RPLI + c * VDI \tag{7}$$

Where, a = 0.4, b = 0.3 and c = 0.3 are the weightage indices.

These weights represent the priority given for each index for the integration of DGs with different load models. The values of weights for the indices are selected based on the literature in [11,17]. The values may be chosen different values based on the priority of researcher in penetrating the DG.

Constraints

The bus voltage of RDS should be within the safest specified limit even after the DG integration and also the size of real and reactive power of DG should be less than the total load of RDS. Hence, the following constraints are defined to prevent the system diverting from safe operating mode and it is expressed in Eqs. (8) - (10):

$$V_i^{Min} \le |V_i| \le V_i^{Max} \tag{8}$$

$$P_{DG}^{Min} \le P_{DG} \le P_{DG}^{Max} \tag{9}$$

$$Q_{DG}^{Min} \le Q_{DG} \le Q_{DG}^{Max} \tag{10}$$

Load models

The OPDG solution is depend upon the type of the load and also the impact will be different. This has been investigated by considering various voltage-dependent load types such as constant (Con), residential (Res), commercial (Com) and Industrial (Ind). The real and reactive loads at each bus j changes with respect to voltage at the same bus with an exponential value a and b are mathematical expressed in Eqs. (11) and (12).

$$P_j = P_{oj}V_j^{\alpha} \tag{11}$$

$$Q_J = Q_{oj}V_j^{\beta} \tag{12}$$

Where P_j and Q_j are the active and reactive power at node j, P_{oj} and Q_{oj} are the operating active and reactive power at node j, V_j is the voltage at node j. where α and β are the exponent of active and reactive power.

The value of α and β is 0 for conventional constant power load. The exponential values of α and β for different types of loads are summarized in **Table 1** [4,5]. The real-world scenario is different where the load is combination of all types. Therefore, the investigation also extended to mixed (Mix) load where all the load models were considered in equal proposition.

Table 1 relationship values of voltage-dependent load models.

Load Type	α	β
Con	0	0
Res	0.92	4.04
Com	1.51	3.4
Ind	0.18	6

Harmonic load flow analysis

The impacts of size and site of multiple DGs obtained by the proposed algorithm on voltage THD of the system is evaluated by using direct approach called forward/backward sweep technique based harmonic flow analysis [22]. Randomly the location of non-linear loads is selected as harmonic sources to carry out the analysis. In this method, the relationship between bus voltage, branch current and bus current injection is derived to compute all order harmonic. The **Figure 1** represents the steps involved in the process. The detailed step by step procedure of frequency scan based harmonic flow analysis is presented in [22].

ABC-HC algorithm

The hybrid ABC-HL algorithm approach includes the positives of both the algorithm which yields a solution which is more fit to the given fitness function. In the proposed algorithm the local search algorithm called Hill climbing method is employed for local search and ABC is used for global search, together to find the optimal solution for the problem. The architectural structure of hybrid ABC-HC method is presented in **Figure 2** and explained as follows:

Step1: Run Base case load flow and obtained the fitness value

Step 2: Initialize the size, site and number of DGs using hybrid algorithm

Step 3: Run a load flow with DGs and obtain the fitness value

Step 4: Evaluate the fitness function and if it is fit the size, site and number of DGs are taken as optimal solution or else the solution will be updated.

Step 5: The process repeats for n number of iterations.

Artificial bee colony

In 2005, Karaboga, put forward meta heuristic ABC to solve real time optimization problems. The intelligence of honey bee inspires the author to develop this algorithm. The optimal solution will be found out by 3 kinds of bees i.e. employed bees, onlookers and scouts. Bee colony consist of equal population of employer and onlooker bees. The solution to the problem is represented by the food source position and the quality (fitness) of that solution is represented by the amount of food source nectar. The number of solutions is described by the employed bee population meanwhile each working bee represents only one solution. Generally, ABC method involves employed and onlooker bees to carry out local search, and onlookers and scouts for global search, performing balanced investigation throughout the process [18,19].
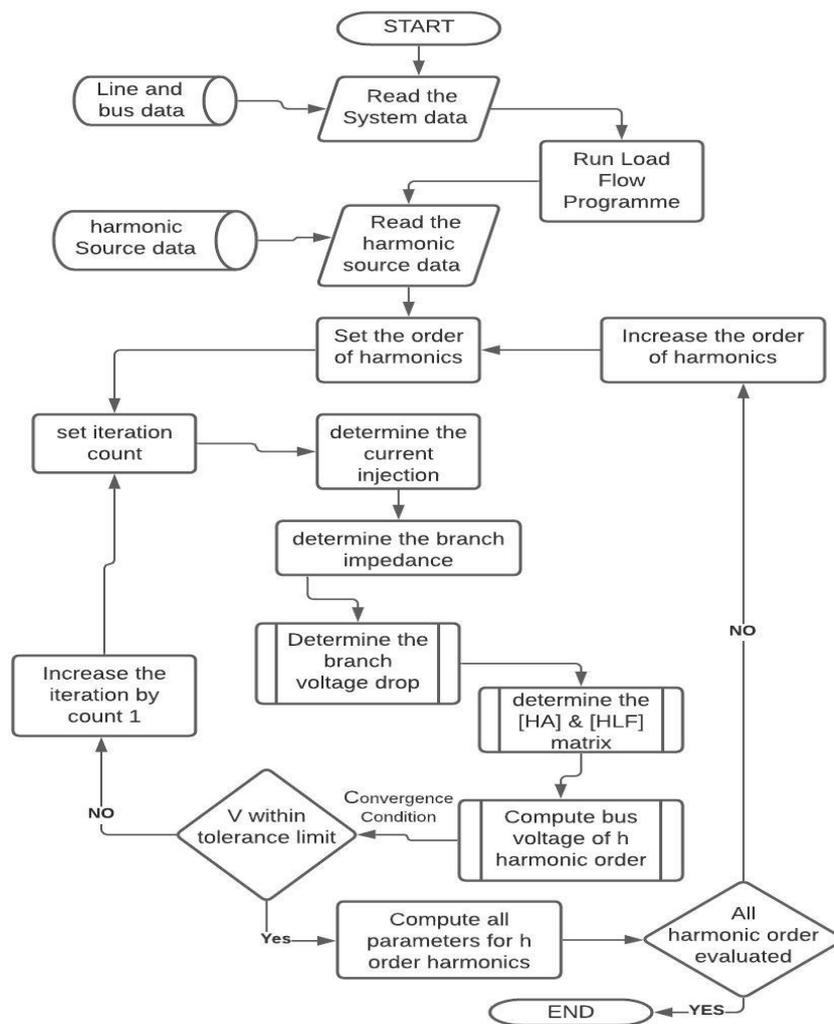

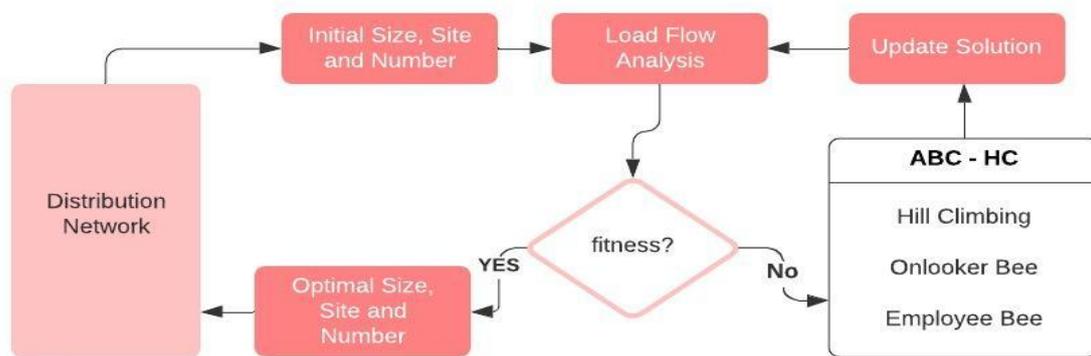**Figure 1** Flow chart of harmonic flow analysis.

Figure 2 Architecture of the ABC-HC.

The various working stages of ABC involves Initialization, working Bee searching phase, onlooker bee searching phase, scout bee searching phase, selection of food source and termination of the process as discussed in [21]. The onlooker bee selects a food source in the probability of P_f and is computed using Eq. (13).

$$P_f = \frac{fitness}{\sum_{f=1}^{E_b} fitness_f} \tag{13}$$

Where $fitness_f$ is the fitness value of a solution f, E_b is the total number of solutions.

The termination condition for the searching process is specified by maximum number of iterations. Ultimately the best solution is selected as the optimal solution for the problem.

Hill climbing algorithm

A local search optimization technique called simple hill Climbing algorithm is used to find local best solution for the real-world problems. It continuously searches for the path to move towards the best solution to the problem and it terminates when it reaches a peak value. In this algorithm, the current node state compares with neighbor node state and picks the better state as optimal solution. Each node consisting of state and value. The algorithm for simple hill climbing as shown in **Figure 3**.

Step 1: Initial solution
Step 2: While f(s) ≤ f(i) s € Neighbours (i);
Step 3: Generates an s € neighbours (i);
Step 4: If fitness(s) > fitness (i) then
Step 5: Replace s with I;
Step 6: End If

Figure 3 The working flow of ABC.

Results and discussion

The evaluation of performance and robustness of the proposed method is demonstrated on IEEE 33-bus RDS with a base of 100 MVA. In this study, along with constant power load, 3 different voltage-dependent loads are modeled and also considered the mixed load profile. The test system consists of 33 bus, 32 branches and 12.66 kV voltage. The SLD of the considered test system is shown in **Figure 4**. The line and bus data are given in Sahoo and Prasad (2006). The total active and reactive power load of the system is depending on the node voltage. The total size of DG is limited to maximum load capacity of the system. This algorithm is programmed in MATLAB 2017a.

The work carried out is presented in 2 different sections as follows:

    Section 1: Optimal planning of single as well as multiple DGs using proposed ABC-HC algorithm

    Section 2: The effect of linear DG integration on the voltage THD of the distribution network using fast harmonic flow analysis [21].
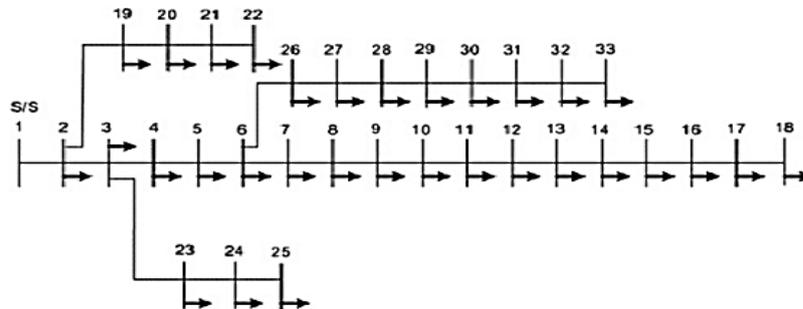

Figure 4 SLD of IEEE 33-bus RDS.

Section 1: Optimal planning of single as well as multiple DGs using proposed ABC-HC algorithm

    The optimal location and rating of single and multiple DG based on multi-objective fitness function for different voltage dependent load model is summarized in **Tables 2 - 6**. The NRLF approach is employed to obtain base case active power loss and is 250.84, 160.67, 153.57, 121.6 and 183.89 kW for cons, Res, Com, Ind and Mix load, respectively. The proposed approach significantly reduces the real power loss by 68.86, 68.22, 66.627, 66.35 and 69.93 % and reactive power loss by 65.86, 64.63, 62.89, 62.06 and 66.31 % for the above said load models when single DG is optimally integrated. The active line loss reduction increased to 75.46, 73.59, 71.87, 73.375 and 74.52 % and reactive loss reduction increased to 71.58, 69.46, 68.42, 68.87 and 70.60 % for considered loads when multiple DGs are optimally integrated. Irrespective of the load type, the TVDI is reduced to 0 it represents significant increase in the node voltage and also it shows that the magnitude of all the bus voltage is in the range of 0.95 to 1.05 pu as shown in **Figure 7**. Therefore, the performance of this technique has been substantially reducing the line losses and TVD of the distribution network. The active and reactive power loss of RDS for considered load models before and after integration of single and multiple DGs are shown in **Figures 5** and **6**, respectively and it was observed that the integration of DGs reduces line losses for all type of loads. From **Tables 2 - 6**, the OPDG solution is diverse for different types of load and also it can be noticed that the constant power load requires large rating DG compare to voltage-dependent load models to obtain the best possible solution for the said problem statement.
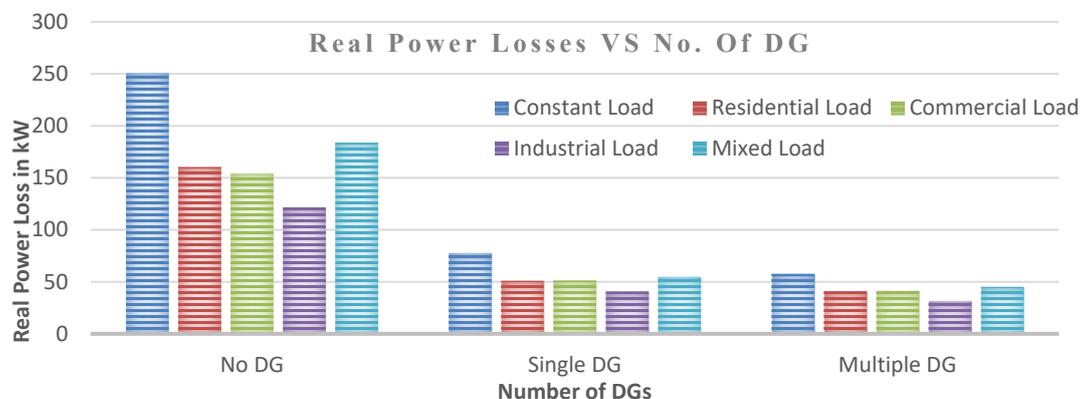

Figure 5 Active power loss for considered load models with and without DGs.
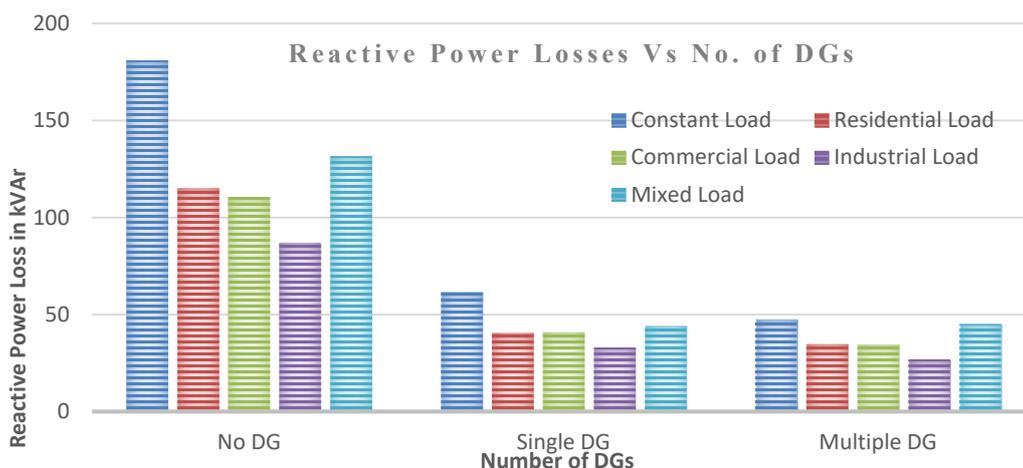
Figure 6 Reactive power loss for considered load models with and without DGs.

Table 2 OPDG for constant load model.

Parameters	Without DG	With DG					
	Base Case	Single DG		Multiple DG			
Optimal Site & rating of DG in MW and MVAr	-	14	1.5295	0.9478	8 14 9	0.5552 1.375 0.249	0.3441 0.8522 0.1543
Total rating of DG	-	-	1.5295	0.9478	-	2.1792	1.3506
P_{loss} in kW	250.84	78.1	-	-	61.54	-	-
Q_{loss} kVAr	180.89	61.75	-	-	51.41	-	-
% reduction in P_{loss}	-	68.86	-	-	75.46	-	-
% reduction in Q_{loss}	-	65.86	-	-	71.58	-	-
TVDI	0.6569	0	-	-	0	-	-
Minimum Voltage (pu)	0.911 @ bus 18	0.9842 @ bus 21		0.9845 @ bus 21			

Table 3 OPDG for residential load model.

Parameters	Base Case	With DG					
		Single DG		Multiple DG			
Optimal Site & rating of DG in MW and MVAr	-	14	1.139141	0.705976	14 12 6	0.8126 0.1379 0.4886	0.5036 0.0854 0.3028
Total rating of DG	-	-	1.139141	0.705976	-	1.4391	0.8918
P_{loss} in kW	160.67	51.06	-	-	42.43	-	-
Q_{loss} kVAr	114.9	40.64	-	-	35.09	-	-
% reduction in P_{loss}	NA	68.22	-	-	73.59	-	-
% reduction in Q_{loss}	NA	64.63	-	-	69.46	-	-
TVDI	0.3806	0	-	-	0	-	-
Minimum Voltage (pu)	0.9304 @ bus 18	0.9852 @ bus 22		0.9857 @ bus 21			

Table 4 OPDG for commercial load model.

Parameters	Base Case	With DG					
		Single DG			Multiple DG		
Optimal Site & rating of DG in MW and MVAr	-	14	1.195478	0.740891	14	0.7755	0.4806
					6	0.4588	0.2843
					10	0.276	0.171
Total rating of DG	-	-	1.195478	0.740891	-	1.5103	0.9359
P_{loss} in kW	153.75	51.31	-	-	43.24	-	-
Q_{loss} kVAr	110.61	41.04	-	-	34.93	-	-
% reduction in P_{loss}	-	66.627	-	-	71.87	-	-
% reduction in Q_{loss}	-	62.89	-	-	68.42	-	-
TVDI	0.3603	0	-	-	0	-	-
Minimum Voltage (pu)	0.9339 @ bus 18	0.9851 @ bus 21			0.9852 @ bus 22		

Table 5 OPDG for industrial load model.

Parameters	Base Case	With DG					
		Single DG			Multiple DG		
Optimal Site & rating of DG in MW and MVAr	-	14	1.0118	0.6271	11	0.2628	0.1628
					6	0.5722	0.3546
					14	0.6956	0.4311
Total rating of DG	-	-	1.0118	0.6271	-	1.5306	0.9485
P_{loss} in kW	121.66	40.94	-	-	32.39	-	-
Q_{loss} kVAr	87.07	33.03	-	-	27.1	-	-
% reduction in P_{loss}	-	66.35	-	-	73.37	-	-
% reduction in Q_{loss}	-	62.06	-	-	68.87	-	-
TVDI	0.2746	0	-	-	0	-	-
Minimum Voltage (pu)	0.9414 @ bus 18	0.9857 @ bus 21			0.986 @ bus 21		

Table 6 OPDG for mixed load model.

Parameters	Base Case	With DG					
		Single DG			Multiple DG		
Optimal Site & rating of DG in MW and MVAr	-	14	1.2729	0.7888	5	0.4168	0.2583
					14	1.043	0.6467
					6	0.3238	0.2007
Total rating of DG	-	-	1.2729	0.7888	-	1.7836	1.1057
P_{loss} in kW	183.89	55.29	-	-	46.86	-	-
Q_{loss} kVAr	131.56	44.32	-	-	38.67	-	-
% reduction in P_{loss}	-	69.93	-	-	74.52	-	-
% reduction in Q_{loss}	-	66.31	-	-	70.60	-	-
TVDI	0.2746	0	-	-	0	-	-
Minimum Voltage (pu)	0.9243 @ bus 18	0.9851 @ bus 21			0.9854 @ bus 21		

The TVDI has been nullified successfully by installing multiple DGs at potential locations. The **Figure 7** graphically represents the improvement of voltage profile of RDS for all studied load models. The minimum voltage without DG at bus 18 is 0.91 pu for Con load, 0.9304 pu for Res load, 0.9339 pu for Com load, 0.9414 for Ind load and 0.9243 for Mix load and the integration of single and multiple DGs into RDS effectively enhanced the voltage profile of the system.
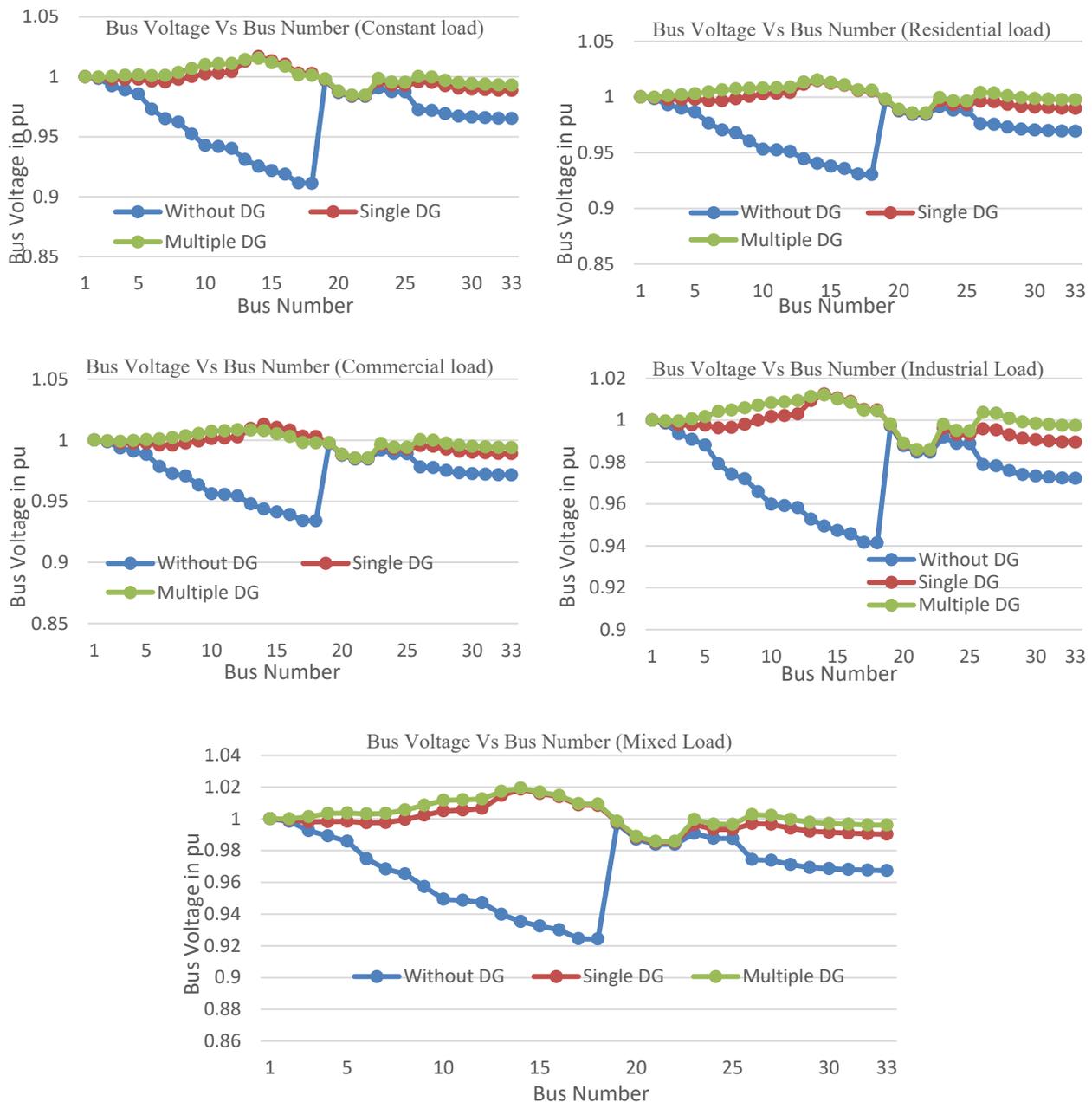

**Figure 7** The voltage profile of RDS for different loads.

The results of the proposed technique were directly compared against published work in literature within the related arena in **Table 7**. It reveals that for the same objective function, the proposed technique is more promising in line losses reduction and minimization of TVD of the system compare to other methods which was found in literature.

Table 7 Comparison of results with different algorithm.

Algorithm	Year	DGs' Sizes (MW)	DGs' Location	P_{Loss} reduction (%)	V_{worst}, bus (pu)
CSCA [3]	2020	0.871, 1.09147, 0.95408	13, 24, 30	64.5	0.9690
GSA-GAMS [7]	2019	0.80122, 1.0913, 1.05359	13, 24, 30	65.64	0.9686
SSA [1]	2019	0.7536, 1.1004, 1.0706	13, 23, 29	64.73	0.9686(33)
FWA [14]	2019	0.5897, 0.1895, 1.0146	14, 18, 32	56.24	0.9680
SPEA2 [16]	2018	0.691, 0.7334, 0.7429	18, 29, 8	71.1	0.9616
ABC-CS [13]	2017	0.78, 0.84, 1.12	13, 25, 30	64.8	0.9756(33)
NLSA [15]	2017	0.750, 1.070, 1.040	14, 24, 30	65.5	0.9669
ACO-ABC [4]	2016	0.7547, 1.0999, 1.0714	14, 24, 30	62.8	0.9735
IWO [11]	2016	0.6247, 0.1049, 1.056	14, 18, 32	57.7	0.9716
BSOA [9]	2015	0.632, 0.487, 0.550	13, 28, 31	56.1	0.9554
BFOA [5]	2014	0.633, 0.090, 0.947	17, 18, 33	51.5	0.964
GA-PSO [6]	2012	0.925, 0.863, 1.200	11, 16, 32	49.2	0.967
IWD [10]	2011	0.6003, 0.300, 1.0112	9, 16, 30	`57.7	0.9696
Proposed ABC-HC	**2020**	**0.5552, 1.375, 0.249**	**8, 14, 9**	**75.46**	**0.9845(21)**

Scenario 2: The effect of linear DGs on voltage harmonics of RDS

The evaluation of findings of the proposed technique corresponding to THD, the harmonic load flow analysis is carried out in time domain on IEEE 33-bus RDS. The nonlinear loads HVDC - 6 pulse converter and SVC are modelled and considered at bus 17 and bus 25, respectively as harmonic current source [21]. The harmonic sources inject 5th, 7th, 11th, 13th and 15th order harmonics. The harmonic voltage at each bus before and after integration of multiple DGs for constant load are shown in **Figure 9** and it can be observed that the findings of section 1 are promising in reducing the magnitude of harmonic voltage compare to base case for all load models. The **Figure 8** clearly shows that the % THD of voltage at each bus are within the standard limits ±5 % and also the THD percentage has been reduced due to optimal integration of multiple DGs.
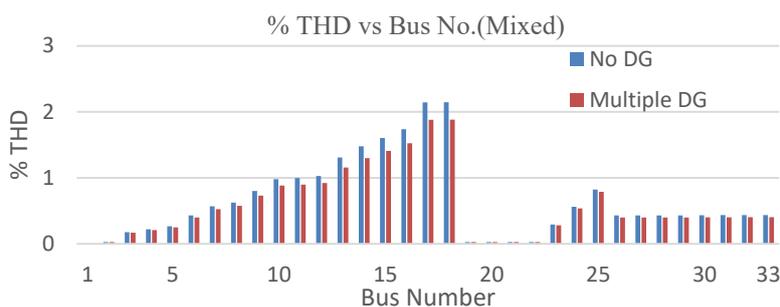
% THD vs Bus No.(Mixed)

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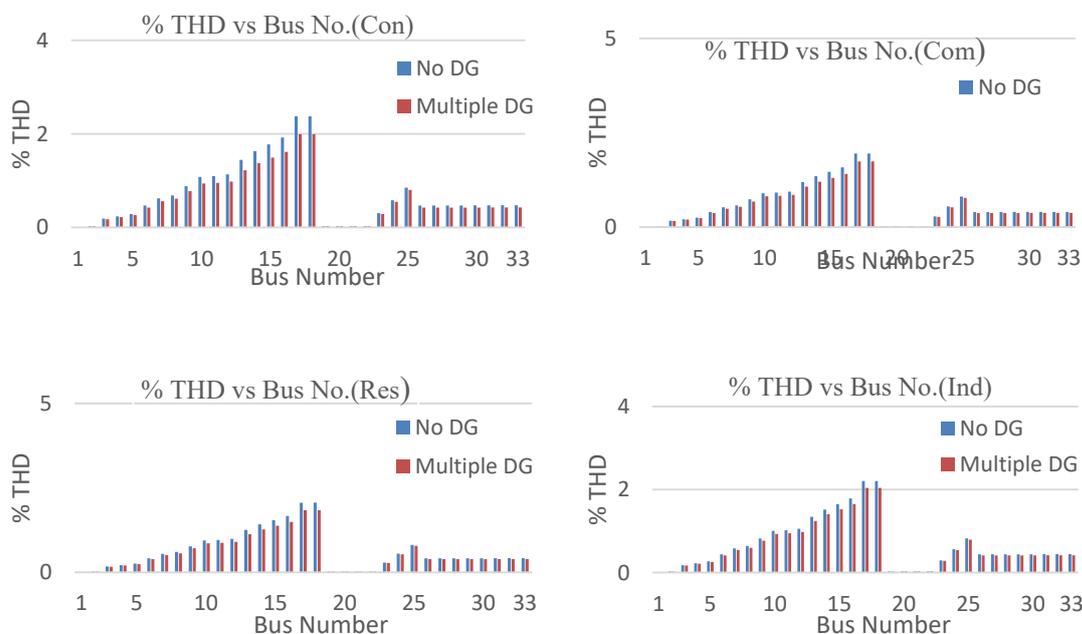
Figure 8 Effect on % THD of RDS for different load models.

The harmonic voltage at each bus of different orders for constant load before and after placement of multiple DG are demonstrated graphically in **Figures 9 - 10** and it can be found that the magnitude of harmonic voltage is gradually decreasing in increase in harmonic order and this argument are in line with results reported in literature [20].
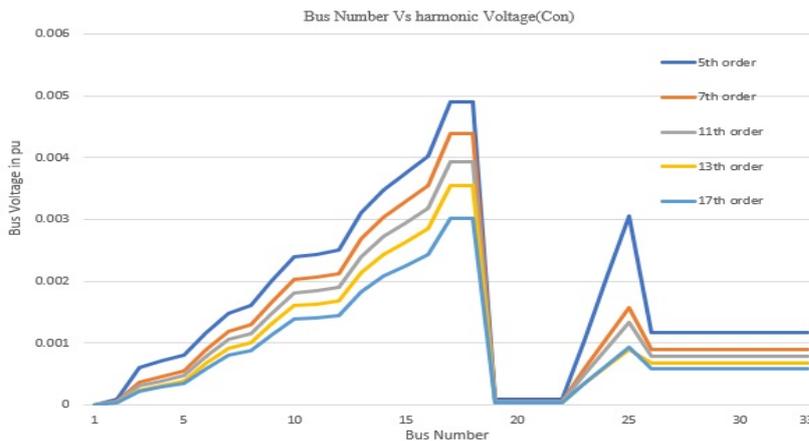

Figure 9 Harmonic voltage at each bus of different orders before DG for constant load.
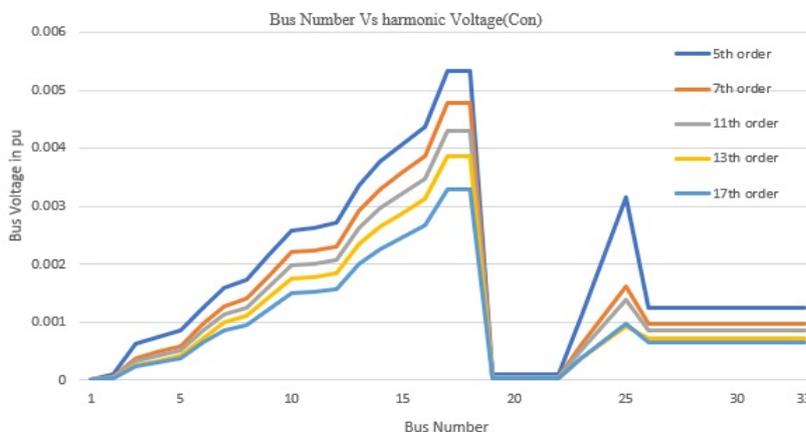

Figure 10 Harmonic voltage at each bus of different orders after DG for constant load.

Conclusions

The optimal solution for multiple DG placement is addressed by using a novel hybrid ABC-HC algorithm considering multi-objective function which includes minimization of real and reactive power losses and total voltage deviation with the help of indices for different load models. The performance evaluation was demonstrated on IEEE 33-bus RDS. The base case NRLF shows that the power losses and voltage profile are different for different load models and also the rating and siting of multiple DGs is different for considered various load types. The size of the DGs is larger for constant load type compare to practical load types to extract the maximum benefit of DGs. The result presents that the integration of DGs significantly reduces the line losses and improves the voltage profile of the system for all the load models. Also, the harmonic flow analysis has been carried out to assess the influence of DG rating and location on voltage THD. It can be noticed that the integration of linear DGs with distribution network reduces the THD level and improves the voltage profile in all considered the load type.

Acknowledgements

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