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RESEARCH ARTICLE - ELECTRICAL ENGINEERING

Optimal Placement and Sizing of DER's with Load Variations Using Bat Algorithm

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Abstract This paper presents an algorithm for optimal placement and size of the distributed energy resources (DERs) considering loss minimization, voltage profile improvement, and line flow capacity as multi-objectives. DERs are the energy resources which contain renewable energy resources such as wind, solar and fuel cell, and some artificial models such as microturbines, gas turbines, diesel engines, sterling engines, and internal combustion reciprocating engines. Combinations of DER studies and for every combination, indices, active and reactive losses, and voltage profiles are studied. To optimize the objective function, new optimization technique called Bat algorithm (BA) is proposed. The work is tested on 38-bus distribution system with different % of loading such as 90, 100, and 110 % of base-load condition. With BA, the voltage profile of the system and loss reduction with different loading conditions are presented. For all cases, current injection-based distribution load flow method is used.

Keywords Distributed energy resource (DER) · Distribution systemloading · Loss minimization · Optimization algorithm · Bat algorithm

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الخلاصة

تعرض هذه الورقة العلمية خوارزمية للحجم والتوظيف المثاليين لمصادر الطاقة الموزعة وتأخذ بعين الاعتبار: تقليل الفقد، وتحسين ملامح الجهد، وسعة تدفق الخط بوصفها متعددة الأهداف. إن مصادر الطاقة الموزعة هي مصادر الطاقة التي تشمل مصادر متجددة للطاقة مثل الرياح والطاقة الشمسية وخلايا الوقود وبعض النماذج الاصطناعية مثل التوربينات الميكروية وتوربينات الغاز ومحركات الديزل ومحركات الاسترليني ومحركات الاحتراق الداخلي الترددية. وقد تمت دراسة مجموعات من مصادر الطاقة الموزعة ولكل مجموعة تمت دراسة الأرقام القياسية والخسائر الفعالة والمتفاعلة وملامح الجهد. واقُترحت تقنية أمثلة جديدة من أجل أمثلة دالة الهدف تسمى خوارزمية الخفاش. واختُبِر العمل على نظام توزيع ناقل-38 مع اختلاف % من الحمل مثل 90% و100% و110% من شرط حمل القاعدة. وباستخدام خوارزمية الخفاش تم عرض ملامح الجهد للنظام وتقليل الفقد مع شروط حمل مختلفة. وتم أيضاً استخدام طريقة تدفق حمل التوزيع المعتمدة على حقن التيار لجميع الحالات.

List of symbols

Parameters

OF	Objective function
IC	Line flow Index
IVD	Voltage profile Index
V1	Reference voltage bus
V_i	Voltage of the ith bus including DER
V_{imin}	Minimum bus voltage at bus 'i'
V_{imax}	Maximum bus voltage at bus 'i'
n	number of busses
S_j	Jth line flow
CS_j	maximum flow capacity of line'j'
Pgs	Substation bus power
m	number of DERs
P_{DER}	Active power generated by DER
P_{load}	Total system load
$P_{load,i}$	Active power load at bus 'i'
$P_{DER,I}$	Active power generated by DER at bus 'i'
$Q_{load,I}$	Reactive power load at bus 'i'

$Q_{DER,I}$	Reactive power generated by DER at bus 'i'
P_{loss}	Total system active power loss
nline	Number of lines
P_{DERi}	Active power injected by DER in bus 'i'
$TP_{lossDER}$	Total active power loss with DER
$TQ_{lossDER}$	Total reactive power loss with DER
$TP_{lossWODER}$	Total active power loss without DER
$TQ_{lossWODER}$	Total reactive power loss without DER
ILP	Active power loss Index
ILQ	Reactive power loss Index
IVD	Voltage profile Index
IC	MVA capacity Index of line
A	Loudness of Bat
r	Pulse emission rate of Bat

1 Introduction

The distributed energy resource (DER) is the electricity generated at consumer end and thereby reduces the problem associated with transmission and distribution losses, costs, saving of the fuel, reduction of sound pollution and green house gases, unreliability of the grid, and the problem of remote and inaccessible regions [1]. Other benefits include peak load shaving (energy outflows from DERs during demand peaks), better voltage profile, relieving of transmission and distribution congestion then improved network capacity, protection selectivity, network robustness, and islanding operations [2,3]. In India, DER technologies are encouraged in the electrified villages, where many are dissatisfied with the quality of grid power.

The more common DER technologies available in India are microturbines, wind turbines, biomass, and gasification of biomass, solar photovoltaic's, and hybrid systems. However, most of the plants are based on wind power, solar, Hydel power and biomass, and biomass gasification. The technology of solar photovoltaic's, wind power is costly and nature dependent. The fuel cells and microturbines are yet to be commercialized in many countries like India

The maximum benefits of DER and the impact of DER on power losses are not only affected by DER location but also depends on the network topology as well as on DER size and type [1]. Influence of DER on transmission congestion also depends on location of DER in distribution system. Strategically located DER units may utilize the upstream transmission system less, if opportunely operated, and thereby helping to relieve congestion in the transmission network. For better understanding, efficient and robust operation of DERs, and for incorporating DERs in load flow studies and for Distribution Automation and Demand Side Management, the mathematical modeling is very essential. For different type of DERs, separate mathematical modeling is required. Literature in [4–7] is available for different DER models in distribution system load flow.

Akorede et al. [1] presents a review of different optimization techniques for optimal placement and size of the DER. In the papers [4–8], DERs are modeled as constant power injection source and multiple DERs are not considered. Singh et al. [9] have discussed the size and location of the DER for 'different load models', but offered no details about the multiple DER placement and size and type of DERs. Further, the DER is modeled as unity power factor source with fixed rating at 0.63 p.u for all studies. In this present work, the objective was to optimize DER location and size, while minimizing system real, reactive losses and to improve voltage profile. In the present work, four types of DERs (solar, wind mill, fuel cell, and microturbine) are considered for modeling and incorporating to testing the proposed algorithm. In this paper, the DERs are modeled in current injection-based load flow (CILF), which is very efficient for distribution systems [10]. The renewable DERs wind and solar are modeled as constant power factor (p.f) model and variable reactive power model in CILF, and microturbine and fuel cell are modeled as negative load model and constant voltage model, respectively.

Various impact indices are studied in this paper. The indices are developed in view of improving the system performance by decreasing the losses and improve the voltage profile of network. For finding the optimal solution by minimizing the impact indices, a new Bat algorithm (BA) is used. The BA is a real-coded population-based meta-heuristic optimization method that mimics the mimetic evolution of a group of Bats when seeking for the location that has the maximum amount of available food [11]. It is the combined algorithm of the local search tool of the PSO and mixing information from parallel local searches to move toward a global solution. The whole work is done for different load models such as residential, industrial, commercial, and mixed load.

2 Impact Indices and Objective Function

2.1 Impact Indices

1) *Real and Reactive loss indices (ILP and ILQ)*
   The active and reactive losses are greatly depending on the proper location and size of the DGs. The indices are defined as

$$ILP = \left(\frac{TPlossDER}{TPlossWODER}\right) \tag{1}$$

$$ILQ = \left(\frac{TQlossDG}{TQlossWODG}\right) \tag{2}$$

2) Voltage profile Index (IVD) [12]

$$IVD = \underset{i=2}{\overset{n}{Max}} \left(\frac{|V1| - |Vi|}{|V1|} \right) \tag{3}$$

The voltage profile of the system is depending on the proper location and size of the DGs. The IVD is defined as.

3) MVA capacity Index (IC) [12]
The IC Index gives the important information about the line of MVA flow through the network regarding the maximum capacity of conductors. The IC can be defined as

$$IC = \max_{j=1}^{nl} \left(\frac{|Sj|}{|CSj|} \right) \tag{4}$$

This Index penalizes the size and location pair, which gives higher flow deviation of the line from the MVA capacity of the line, hence make the uniform line flows in the system without congestion.

2.2 Objective Function

The main objective of this paper was to study the effect of placing and sizing the DG in all system indices given previously. Also observe the study with renewable bus available limits. Multi-objective optimization is formed by combining the all indices with appropriate weights. The multi-objective function is defined as

$$OF = (W_1 * ILP + W_2 * ILQ + W_3 * IC + W_4 * IVD) \tag{5}$$

To convert multi-objective function into single objective, weights are added. The weights are taken from reference paper [11]. In this paper, the weight is considered [11] as W1 = 0.4, W2 = 0.2, W3 = 0.25 and W4 = 0.15 (for better objective function, weights are adjusted by trial and error method) and by taking into account constraint

$$where \quad W_k \in [0, 1] \qquad \sum_{k=1}^{4} W_k = 1$$

The weights are indicated to give the corresponding importance to each impact indices for the penetration of DGs and depend on the required analysis. In this analysis, active power losses have higher weight (0.4), since the main importance is given to active power with integration of DG. The least weight is given to the IVD, since the IVD is normally small and within permissible limits. The OF (5) is to minimize with equality and inequality constraints.

Equality constraints

$$Pgs + \sum_{DER=1}^{m} P_{DER} = P_{load} + P_{loss} \tag{6}$$

Inequality constraints

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

3 Bat Optimization Algorithm

The BA is a real-coded population-based meta-heuristic optimization method that mimics the mimetic evolution of a group of Bats when seeking for the location that has the maximum amount of available food. The echolocations of microbats are the feasible solutions. It is based on frequency-tuning technique to control the dynamic behavior of a swarm of Bats, i.e., evolution of group of Bats carried by the interactive individuals and a global exchange of information among themselves [12]. In essence, it combines the benefits of the local search tool of the PSO [13] and mixing information from parallel local searches to move toward a global solution [14]. PSO is an evolutionary optimization method, which is based on the metaphor of social interaction and communication such as bird flocking and fish schooling. PSO is initialized with random solutions (swarm), every individual or potential solution, called Particle, flies in the dimensional problem space with a velocity which is dynamically adjusted according to the flying experiences of its own and its social group [15]. In the BA, the population consists of a set of Bats with the same structure but different adaptabilities. Virtual bat flies randomly with a velocity (Vi) at position (solution) (Xi) with a varying frequency or wavelength and loudness (A). As it searches and finds its prey, it changes frequency, loudness (A), and pulse emission rate (r) [11].

3.1 Overview of BA

Assume that the initial population is formed by generating ‘B’ Bats randomly. pop (i), i = 1,2,…., B. Evaluate the fitness fit(i) of ith Bat and arrange the Bats in ascending order of their fit values. The Fth Bat will have the highest fitness value and first Bat will be with lowest fitness value. For every population, the best value will appear as the last entry and is named as ‘best’. Each bat updated with their loudness (A) and rate (r) [10].

3.2 Bat(solution) Update

If the problem not converged in first iteration, it needs to go for further population. The convergence criteria have used in this paper are maximum number of iterations. For every population, the fitness function is updated with local exploration search and check the loudness is within the limits or not. If the Bat loudness is within the limit, then solution is updated for that bat. If the bat loudness is not in the limits, then the bat is fixed with their limits by adding some penalty factor. For every population, rate and fitness of bat are updating. The bat's having rate more than required rate are penalized by rate factor. The flow chat shows the detailed procedure of BA.

4 Modeling of DERs in Load Flow Studies

In system with DERs, the generation of photovoltaic systems, fuel cells, microturbines, and some wind turbine units are injected into the power grid via power electronic interfaces. In such cases, the model of a DER unit in load flows depends on the control method, which is used in the converter control circuit. The DERs that have control over the voltage by regulating excitation voltage (synchronous generator DERs) or by the 'P' and 'V' independently controlled converter circuit, and then the DER unit may be model as PV type. Other DERs like induction generator-based units or 'P' and 'Q' independently controlled converter are shall be modeled as PQ type. Using these models for DERs, current injection-based load flow method is employed for distribution system studies.

4.1 Current Injection-Based Load Flow (CILF)

The traditional load flow methods such as Gauss–Siedel, Newton–Raphson, and fast decoupled techniques are inefficient to solve distribution networks due to the radial structure and wide range of resistance with low X/R ratios. Several methodologies have been proposed to solve the power flow problem in distribution systems such as vector-based distribution load flow, primitive impedance distribution load flow, and forward and backward sweep distribution load flow. But all the methods have limitations like, not applicable for meshed distribution systems and implementation become complex when control devices are present in the system. The CILF [15] can used for both radial and mesh systems and easy to implementation of control devices.

4.2 DER Modeled as PQ Node

A DER unit can be modeled as three different ways in PQ node mode as illustrated below:

1) DER as a 'negative PQ load' model of PQ mode
In this case, the DER is simply modeled as a constant active (P) and reactive (Q) power generating source. The specified values of this DER model are real (P_{DER}) and reactive (Q_{DER}) power output of the DER. It may me noted that fuel cell-type DERs can be modeled as negative PQ load model. The load at bus-i with DER unit is to be modified as

$$P_{load,i} = P_{load,i} - P_{DER,i} \tag{8}$$

$$Q_{load,i} = Q_{load,i} - Q_{DER,i} \tag{9}$$

2) DER as a 'constant power factor' model of PQ mode
The DER is commonly modeled as constant power factor model [16]. Controllable DERs such as synchronous generator-based DERs and power electronic-based units are preferably modeled as constant power factor model. For example, the output power can be adjusted by controlling the exciting current and trigger angles for synchronous generator-based DERs and power electronic-based DERs, respectively [16]. For this model, the specified values are the real power and power factor of the DER. The reactive power of the DER can be calculated by (10), and then the equivalent current injection can be obtained by (11)

$$Q_{iDER} = P_{iDER}\tan(\cos^{-1}(PF_{iDER})) \tag{10}$$

$$\begin{aligned} I_{iDER} &= I^r_{iDER}(V_{iDER}) + jI^i_{iDER}(V_{iDER}) \\ &= \left(\frac{P_{iDER} + jQ_{iDER}}{V_{iDER}}\right)^* \end{aligned} \tag{11}$$

3) DER as 'Variable Reactive Power' model of PQ mode
DERs employing induction generators as the power conversion devices will act mostly like variable reactive power generators. By using the induction generator-based wind turbine as an example, the real power output can be calculated by wind turbine power curve. Then, its reactive power output can be formulated as a function comprising the real power output, bus voltage, generator impedance and so on. However, the reactive power calculation using this approach is cumbersome and difficult to calculate efficiently. From a steady-state view point, reactive power consumed by a wind turbine can be represented as a function of its real power [7], that is

$$Q'_{iDER} = -Q_0 - Q_1P_{iDER} - Q_2P^2_{iDER} \tag{12}$$

where Q'_{iDER} is the reactive power function consumed by the wind turbine. The Q_0, Q_1, and Q_2 are usually obtained experimentally. The reactive power consumed by the load cannot be fully provided by the distribution system, and therefore, capacitor banks are installed for power factor correction, where induction generator-based DERs are employed.

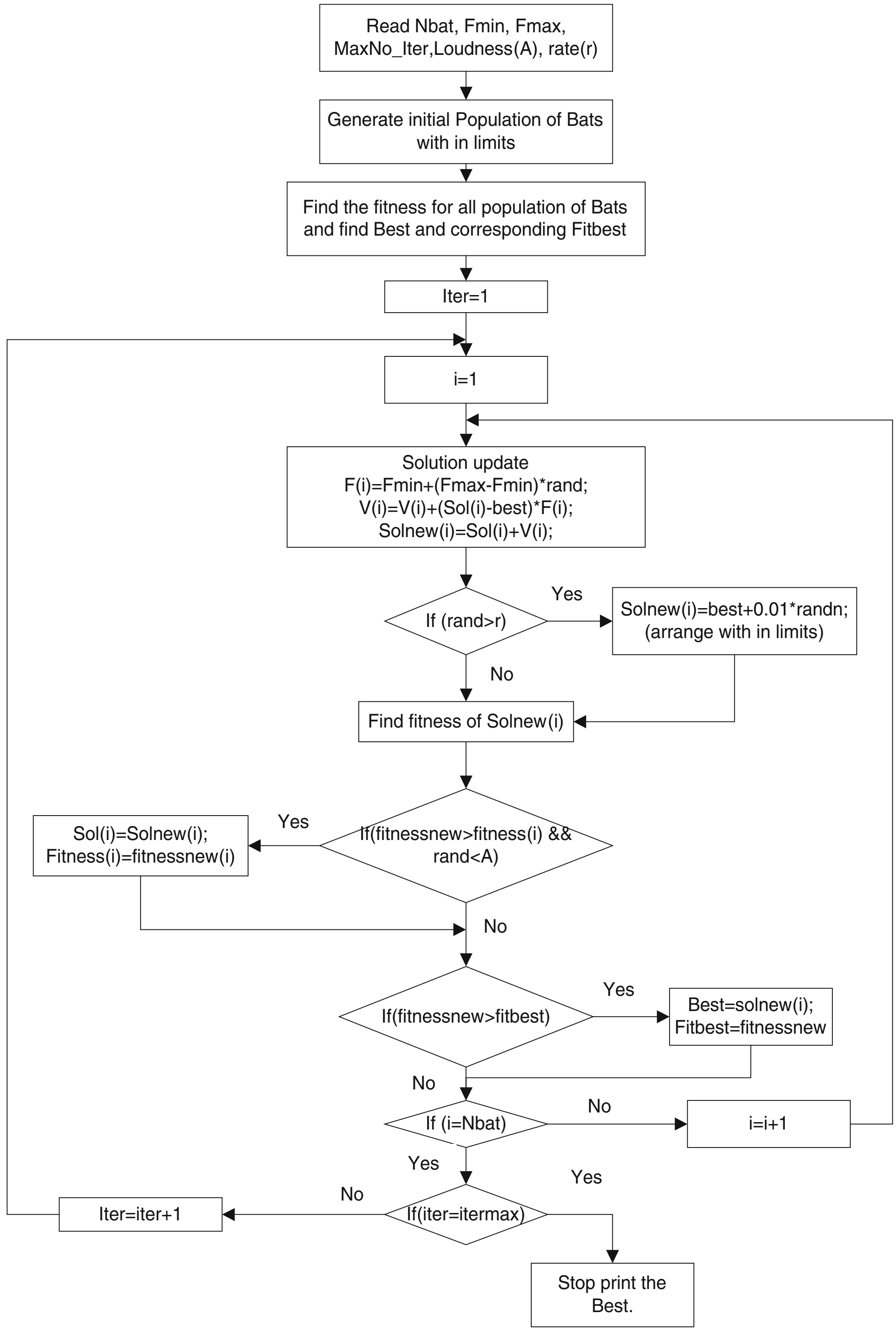

Fig. 1 Optimal place and sizing of the DERs using BA

4.3 DER Modeled as PV Type

The DER as a PV node is commonly constant voltage model. The specified values of this DER model are the real power output and bus voltage magnitude. For maintain constant voltage the, change in voltage ΔV_i should maintain zero by injecting required reactive power.

5 BA Implementation for Optimal Placement and Sizing of DER

In this paper, BA-based optimization technique is used to find the optimal placement and size of the DER by minimizing the losses and voltage improvement. The BA contains 40 Bats. Each Bat contains 20 bits; 8 for placement of the

Table 1 Optimal place and size of the DERs with base load

S.no	Distribution generations type	Optimal DER BUS number	DER value (kW)/ reactive power (kVAR)	Active power loss (kW)	Reactive power loss (kVAR)
1	No DER added (Base Case)			20.221	13.484
2	DER as negative load	14	63	14.28	9.457
3	Solar	31	63/32.27	11.886	7.94
4	Fuel cell	30	63/25.146	14.206	10.03
5	Wind mill	13	47.1	17.652	11.74
6	Neg. load model and solar	13	6275	7.555	4.99
		32	627/32.1		
7	Neg. load model, solar and fuel cell.	31	58.3	2.947	2.06
		14	60.8/31.1		
		30	61.6/11.09		
8	Combination of all 4 DERs	28	57.50	2.890	2.05
		14	54.6/28.0		
		29	59.3/12.63		
		7	46.6/-25.0		

Table 2 Performance indices for base load

	DER as negative load	Solar	Fuel cell	Wind mill	Neg. load model and solar	Neg. load model, solar and fuel cell.	All 4 DERs
ILP	0.7064	0.5878	0.702	0.872	0.3736	0.1457	0.142
ILQ	0.7011	0.5895	0.743	0.871	0.3704	0.1533	0.152
IC	0.9951	0.9998	1.1322	0.995	0.9950	0.9946	0.994
IVD	0.0733	0.0734	0.0539	0.078	0.0429	0.0203	0.0192
OF	0.6825	0.6140	0.7209	0.783	0.4787	0.3406	0.3391

Table 3 Optimal place and size of the DERs with 90 % of base load

S.no	Distribution generations type	Optimal DER BUS number	DER value (kW)/ reactive power (kVAR)	Active power loss (kW)	Reactive power loss (kVAR)
1	No DER added (Base Case)			16.1277	10.752
2	DER as Negative load	14	63	11.1	7.38
3	Solar	31	63/32.27	8.996	6.03
4	Fuel cell	30	63/25.146	10.355	7.32
5	Wind mill	13	47/-25.2	14.029	9.33
6	Neg. load model and solar	13	61.69	5.531	3.66
		31	63/32.27		
7	Neg. load model, solar and fuel cell.	13	62.93	2.296	1.66
		7	62.8/32.2		
		30	60.9/12.1		
8	Combination of all 4 DERs	31	33.4	2.485	1.74
		13	59.7/30.6		
		29	59/11.15		
		11	38.2/-22.0		

Table 4 Performance Indices for 90 % of BaseLoad

	DER as negative load	Solar	Fuel cell	Wind mill	Neg. load model and solar	Neg. load model, solar and fuel cell.	All 4 DERs
ILP	0.6910	0.5578	0.6421	0.8699	0.3429	0.1423	0.1541
ILQ	0.6868	0.5612	0.6811	0.8684	0.3410	0.1552	0.1624
IC	0.8945	0.8953	0.9469	0.8945	0.8941	0.8944	0.8941
IVD	0.0646	0.0642	0.0481	0.0695	0.0377	0.0169	0.0174
OF	0.6470	0.5688	0.637	0.7556	0.4345	0.3140	0.3202

Table 5 Optimal place and size of the DERs with 110 % of base load

S.No	Distribution generations type	Optimal DER BUS Number	DER Value (kW)/reactive power (kVAR)	Active power loss (kW)	Reactive power loss (kVAR)
1	No DER added (base case)			24.8599	16.582
2	DER as negative load	14	63	17.91	11.85
3	Solar	31	63/32.27	15.213	10.15
4	Fuel cell	30	63/28.858	18.838	13.28
5	Wind mill	14	47/-25.2	21.780	14.48
6	Neg. load model and Solar	14	60.07	10.56	6.93
		29	62.9/32.2		
7	Neg. load model, Solar and Fuel cell.	32	62.70	3.839	2.68
		14	60.9/31.2		
		30	62.8/13.61		
8	Combination of All 4 DERs	8	55.09	2.987	2.09
		14	59.0/30.2		
		30	58.0/15.81		
		31	46/-25.1		

DER and remaining 12 are for size of the DER. The information about the DERs is taken by decoding the Bat. The Fig.1 shows the flow chart of optimal place and size of the DER. Matlab programming platform is used for simulation. All DERs are modeled as power system equivalent models, and BAT optimization algorithm is programmed to obtain objective function. Maximum numbers of iterations are limited to 100. In this study, the rate is taken as 0.4 for first population, and it is gradually increased with number of iterations. The loudness value is taken as 0.7. Due to the multi-parallel searches and moving toward global optimum, this BA-based optimization technique can be used for any number of bus systems. The number of Bats, loudness, and rate of the Bats are fixed based on the problem complexity.

6 Results and Validation

For testing the proposed algorithm, the test data of 38-bus distribution systems are considered. In the test data, given load is taken as base load. System data of distribution system are available in paper [17]. The 90 and 110 % of the base load are taken for optimal placement and sizing of DERs at all load variable conditions. Table 1 shows the optimal placement and sizing of DERs with base-load condition. Single DER integration and various combination DERs are also presented in tables. With the maximum number of DERs integration, the active power losses are decreased from 20.221 to 2.890 and reactive power loss from 13.484 to 2.054. Table 2 shows the impact indices of base-loading condition, the lower the indices represent the best performance of the system. The fuel cell integration shows the least performance than the other DERs because it is modeled as constant voltage model. In this constant voltage model, the required p.u voltage at optimal bus is maintained.

Table 5 shows the optimal placement and sizing of DERs with 110 % of base load. With the maximum number of DERs integration, the active power losses are decreased from 24.8599 to 2.987 and reactive power loss from 16.582 to 2.09. In this case also, the placement of the single DERs is

Table 6 Performance indices for 110 % of base load

	DER as negative load	Solar	Fuel cell	Wind mill	Neg. load model and solar	Neg. load model, solar and fuel cell.	All 4 DERs
ILP	0.7206	0.6119	0.7577	0.8761	0.4251	0.1544	0.1201
ILQ	0.7147	0.6123	0.8011	0.8736	0.4180	0.1618	0.1263
IC	1.0959	1.1012	1.3250	1.0959	1.0958	1.0957	1.0956
IVD	0.0821	0.0826	0.0599	0.0874	0.0554	0.0227	0.0215
OF	0.7174	0.6549	0.8035	0.8122	0.5359	0.3714	0.3504

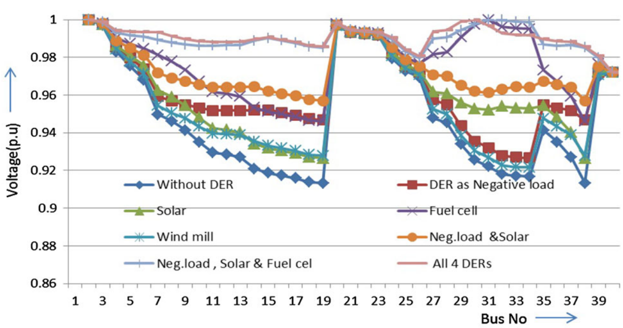

Fig. 2 Voltage profile with combination of DERs for base load

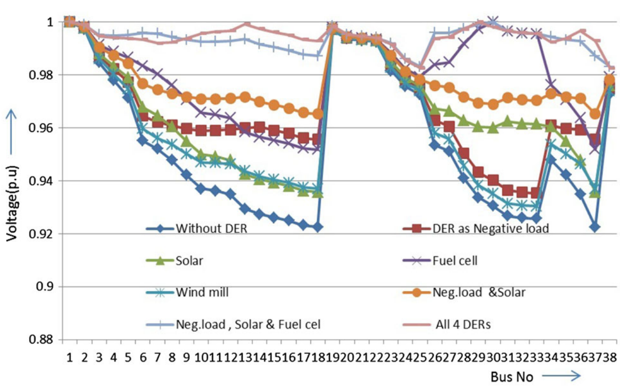

Fig. 3 Voltage profile with combination of DERs for 90 % of base load

almost same of the base case, but in case of multiple DERs, the bus numbers are changing in sensible busses such as 7,11,13,14,28,29,30,31, and 32.

Tables 4 and 6 shows the impact indices for 90 and 110 % of base-load case. With the addition of multiple DERs, the losses are decreasing, but the number of the DERs increased from 3 to 4. The loss reduction ratio is comparatively less in all the load cases; therefore, the DER number is limiting to 4.

Figures 2, 3 and 4 are the voltage profiles of base load, 90 % of base load and 110 % of the base-load conditions. In the base load, the lowest voltage occurred at 19th bus is 0.91p.u. with the decrees of the base loading the voltage profile increased and the 19th bus voltage is improved to

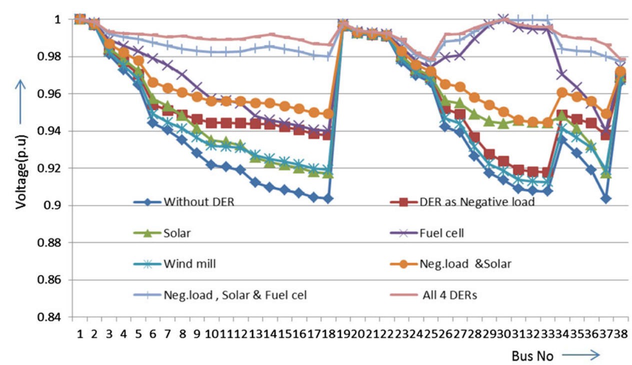

Fig. 4 Voltage profile with combination of DERs for 110 % of base load

0.925p.u. the same bus voltage when 110 % of load condition is again dropped to 0.905p.u. Because of the low variation of the placement of the DERs in 90 % and 110 % of load conditions, the DERs can fix in to the same busses founded in base case.

7 Conclusions

In this paper, an algorithm for optimal placement and size of the DERs is proposed considering system loss minimization and voltage profile improvement as objective functions. The solar and wind systems are modeled as constant power factor model and variable reactive power model and the other two; fuel cell and microturbine are modeled as negative load model and constant voltage model, respectively. Combinations of DERs also studied and for every combination, all indices, active and reactive losses, and voltage profiles are studied. The proposed BA is tested for base load, 90 % of the base load and 110 % of the base load and results are presented. This work is tested on 38-bus distribution systems, and results are found to be satisfactory.

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