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Butterfly optimizer-assisted optimal integration of REDG units in hybrid AC/DC distribution micro-grids based on minimum operational area

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Abstract

This paper presents the impact of optimal location and sizing of renewable and non-renewable-based distributed generators in the AC/DC micro-grid system using the latest optimizer called butterfly optimization algorithm with an aim to minimize power loss. Generally, hybrid AC/DC micro-grids systems are modeled by separating AC and DC feeders with the help of high-power converters (HPC).AC grids sustained by substation and DC grids are maintained by their individual DG units. While planning of DGs in the hybrid AC/DC systems, the power loss incurred by HPCs is not considered avoiding complexity by many authors. In this paper, the sizing of DGs is determined by the operational area required by the type of DG technology as one variable and all possible candidate buses in the respective zones of AC/DC micro-grid system are another variable with due consideration of HPC losses in AC/DC micro-grid system. A hybrid AC/DC MG system is developed by classifying the existing benchmark 33-bus and 69-bus radial distribution systems into various AC/DC zones. To evaluate the proposed approach, it is implemented on aforementioned micro-grid systems and the obtained results are verified with other existing approaches in the literature. The results proved that the proposed approach is better than the other approaches in technical aspects.

Keywords: Butterfly optimizer, REDG units' integration, AC/DC distribution micro-grids, HPC losses, Etc

Introduction

The mass accessibility of sustainable power sources is successfully used in giving uninterruptable power supply to islanded zones. By definition, a micro-grid is an assembly of interconnected dispersed energy sources and loads within clearly defined electrical boundaries that can be operated in a coordinated and controlled way either while connected to the central grid or while island mode [1]. Micro-grids are categorized into AC and DC micro-grids based on the type of power flow and connected loads. The problems associated with AC micro-grids such as reactive power flow, current harmonics, failure of transformers and protection equipment and unbalanced loading of phases create a way to encourage DC micro-grids with DC loads served by dedicated DC sources like

SPVDG (solar photovoltaic-based distributed generator), MTDG (micro-turbine-based distributed generator), FCDG (fuel cell-based distributed generator) and etc. [2]. In general, a distribution system consists of both AC and DC loads and to serve the DC loads connected to the system they must have interfaced through high power converters (AC/DC) which intern contributes harmonic content and conversion losses to the system. To avoid these, DC micro-grid systems are designed and integrated as a part of the AC micro-grid system with the help of HPCs (high-power converter) which can act as an individual grid system and also supports the AC grid system in the case of substation failure to meet the load demand [3].

Optimal allocation of DGs in distribution systems is an attractive research area by considering technical as well as economic benefits which is a nonlinear optimization problem and can be solved by either single objective or multi-objective formulation using any efficient optimizers. In the beginning, many authors proposed solutions for OPDG (optimal placement of DG) problem based on technical benefits such as power loss minimization, voltage profile improvement, reliability improvement and economic benefits like net profit maximization, and minimization of operating cost as an objective functions by considering either DG locations or DG sizes as variables under different load models using GA (genetic algorithm) [4–9], TS (tabu search) [10], PSO (particle swarm optimization) [11, 12], ACO (ant colony optimizer) [13], ABC (artificial bee colony) [14], DE (differential evolution) [15], HS (harmony search) [16], SA (simulated annealing) [17], BS (back tracking search) and BA (bat algorithm) [18], MOIDSA (multi-objective improved differential search algorithm) [19]. The sensitivity approach-based optimal DG allocation methods and its comparison are presented by authors [20, 21]. Optimal allocations of DGs and D-STATCOMs simultaneously in radial distribution systems using PSO algorithms have been presented by authors [22]. The authors presented [23] the allocation of DGs and D-STATCOMs in a radial distribution system using the WDO (wind-driven optimization) algorithm under the daily load pattern. Environmentally committed short-term planning of renewable-based DGs sizing and siting in electrical distribution systems is presented in [24]. The integration of multiple DGs in the islanded operation of distribution systems in a deregulated environment is presented by authors [24, 25].

DGs based on renewable energy are more popular and beneficial, due to abundant availability of sources, the latest advancements in technology and encouragement from the government side. Renewable energy-based DGs are capable of acting as a standalone mode as well as grid-connected mode. This idea leads to the micro-grids concept suggestible not only for rural areas (where the transportation of fuel is difficult) but also for the urban areas to cater to the needs of various customers. So, many researchers have been concentrated on the planning of energy resources in micro-grids for achieving maximum profits. The grid system is always a combination of AC and DC loads. Hence, high-power converters are essential and inevitable to serve DC loads. The utilization of HPC in the AC grid system may increase the system loss level and also injects harmonics into the system. So, DC micro-grids are separated from the AC grid system with the help of HPC's and independent energy sources to cater the needs of particular DC zones. In case, if the AC grid fails to serve the connected load due to some reasons, then DC micro-grid can share the priority loads of AC grid through HPC. Fuel cells can potentially be integrated with solar-PV technology to provide zero-emissions alternatives to fossil fuels. The energy generation cost of solar-PV systems continues to decrease year by year. By extension, hydrogen technologies that run with solar power also become cheaper to operate. Micro-grids with energy storage devices act as energy hubs that can store both electrical and thermal energy to serve the load demand [26]. A two-stage methodology is used to determine optimal locations based on LRSF (loss reduction sensitive factor) and then optimal sizing of REDGs in prefixed locations by using HNMCS algorithm with an objective of minimization of power loss by considering area required by DG type to calculate DG size as variable in AC/DC micro-grids [27] with neglected HPC losses and operating efficiency. In AC/DC networks, HPCs will have a significant role that can control bidirectional power flows. A typical HPC will operate with an average efficiency of 90% remaining 10% is considered as conversion losses [28].

From the literature, it is evident that the optimal allocation of DGs in a distribution system will definitely improve the system performance. Hence, the selection of suitable DG type followed by identifying the optimal size of DG and its placement is a nonlinear optimization problem that can be solved by proper formulation of the objective function and efficient optimizer. This paper presents a methodology to determine optimal allocation of REDGs in AC/DC micro-grid system with an objective of power loss minimization which includes HPC conversion losses by considering not only area required by REDGs to compute the size of REDG but also locations for the integrating REDGs simultaneously as variables using efficient and novel optimizer called butterfly optimizer (BO) to satisfy the AC/DC loads under various system constraints. The proposed methodology is tested on small- and medium-scale hypothetical AC/DC micro-grids under different cases, and obtained results are compared with the existing results from the literature.

Methods

AC load flow model

AC load flow algorithm is performed to calculate the voltage magnitudes of the buses and branch currents of the system. Traditional backward/forward sweep-based load flow has taken as a load flow algorithm.

AC micro-grid with $\mathrm{N_{AC}}$ number of buses, ith bus current $I_{i,\mathrm{AC}}$ is given by

$$I_{i,\mathrm{AC}} = \mathrm{conj}\left(\frac{P_{\mathrm{Li,AC}} + jQ_{\mathrm{Li,AC}}}{V_{i,\mathrm{AC}}}\right) \quad i = 1, 2, \ldots, N_{\mathrm{AC}} \tag{1}$$

where $P_{\mathrm{Li,AC}}$, $Q_{\mathrm{Li,AC}}$ are the active and reactive power demand at ith bus and $V_{i,\mathrm{AC}}$ is the voltage magnitude of an ith bus.

During backward sweep of the backward/forward based load flow, the branch currents are obtained with the help of bus-injections to branch currents matrix (BIBC) as follows

$$J_{k,\mathrm{AC}} = \mathrm{BIBC} * I_i \quad k = 1, 2, \ldots, N_{\mathrm{AC}} - 1 \tag{2}$$

During forward sweep of the backward/forward based load flow, the bus voltages are calculated with the help of branch current to bus voltage matrix (BCBV) as follows:

$$V_{i,\mathrm{AC}} = V_0 - (\mathrm{BCBV}) * J_{k,\mathrm{AC}} \quad i = 2, 3, \ldots, N_{\mathrm{AC}} \tag{3}$$

Repeat Eqs. (2) and (3) until the difference between the voltages of two adjacent iterations is less than the tolerance value (ε).

$$\left| V_{i,\mathrm{AC}}^{\mathrm{itr}+1} - V_{i,\mathrm{AC}}^{\mathrm{itr}} \right| < \varepsilon \tag{4}$$

DC load flow model

DC micro-grid with N_{DC} number of buses, ith bus current $I_{i,\mathrm{DC}}$ is given by

$$I_{i,\mathrm{DC}} = \mathrm{conj}\left(\frac{P_{\mathrm{Li,DCeff}}}{V_{i,\mathrm{DC}}}\right) \quad i = 1, 2, \ldots, N_{\mathrm{DC}} \tag{5}$$

$$P_{\mathrm{Li,DCeff}} = P_{\mathrm{Li,DC}} - P_{\mathrm{REDG}} \tag{6}$$

where $P_{\mathrm{Li,DC}}$, P_{REDG}, $P_{\mathrm{Li,DCeff}}$ are the active power demand, REDG active power and effective active power demand at ith bus, respectively, and $V_{i,\mathrm{DC}}$ is the voltage magnitude of an ith bus.

During backward sweep of the backward/forward based load flow, the branch currents are obtained with the help of bus-injections to branch currents matrix (BIBC) as follows:

$$J_{k,\mathrm{DC}} = \mathrm{BIBC} * I_{i,\mathrm{DC}} \quad k = 1, 2, \ldots, N_{\mathrm{DC}} - 1 \tag{7}$$

During forward sweep of the backward/forward based load flow, the bus voltages are calculated with the help of branch current to bus voltage matrix (BCBV) as follows:

$$V_{i,\mathrm{DC}} = V_0 - (\mathrm{BCBV}) * J_{k,\mathrm{DC}} \quad i = 2, 3, \ldots, N_{\mathrm{DC}} \tag{8}$$

Repeat Eqs. (7) and (8) until the difference between the voltages of two adjacent iterations is less than the tolerance value (ε).

$$\left| V_{i,\mathrm{DC}}^{\mathrm{itr}+1} - V_{i,\mathrm{DC}}^{\mathrm{itr}} \right| < \varepsilon \tag{9}$$

High-power converter (VSC) model

The active (P_{AC}) and reactive (Q_{AC}) power absorbed by HPC from the AC grid with ignored converter losses can be expressed as follows

$$P_{\mathrm{AC}} = \frac{V_{\mathrm{AC}} V_{\mathrm{C}}}{X_{\mathrm{HPC}}} \sin\delta \tag{10}$$

$$Q_{\mathrm{AC}} = \frac{V_{\mathrm{AC}}(V_{\mathrm{AC}} - V_{\mathrm{C}}\cos\delta)}{X_{\mathrm{HPC}}} \tag{11}$$

V_{AC} is the amplitude of AC grid voltage, V_{C} is converter output voltage, X_{HPC} is equivalent reactance of converter, and δ converter modulation angle. However, the converter loss is ignored so that the active power is equal on the AC and DC side. Then the active power can be expressed as

$$P_{\mathrm{AC}} = V_{\mathrm{DC}} I_{\mathrm{DC}} \quad \therefore V_{\mathrm{C}} = \frac{M}{\sqrt{2}} V_{\mathrm{DC}} \tag{12}$$

V_{DC} is voltage on the DC side and M is a modulation index of the converter. Since the power supply on the DC side of the network is poor inactivity, the losses of the converter can be expressed by the current and resistance of the converter as follows

$$P_{C,\,\mathrm{Loss}} = \frac{P_{\mathrm{AC}}^2 + Q_{\mathrm{AC}}^2}{V_{\mathrm{AC}}^2} R = I^2 R \tag{13}$$

where $P_{C,\mathrm{Loss}}$ is power lost in the converter and R is the resistance offered by HPC.

Problem formation

Optimal allocation of REDG units in a hybrid AC/DC micro-grid system is to find the best location as well as the size of REDG units that gives minimum power loss as an objective function with the area required by REDG units as variables while satisfying various operating constraints. The objective function minimization of power loss is described as follows:

$$\mathrm{OF} = \mathrm{Min}\left(P_{T,\mathrm{Loss}}(A_{\mathrm{PV}}, A_{\mathrm{FC}})\right) \tag{14}$$

$$P_{T,\mathrm{Loss}} = \sum_{k=1}^{N_{\mathrm{AC}}} J_{K,\mathrm{AC}}^2 * R_K + \sum_{k=1}^{N_{\mathrm{DC}}} J_{K,\mathrm{DC}}^2 * R_K + P_{C,\mathrm{Loss}} \tag{15}$$

$$P_{\mathrm{REDG}} = (n_{\mathrm{PV}} * I_{\mathrm{PV}} * V_{\mathrm{PV}} * A_{\mathrm{PV}}) + (n_{\mathrm{FC}} * V_{\mathrm{FC}} * A_{\mathrm{FC}} * J) \tag{16}$$

Constraints

Power balance constraint

$$P_{\mathrm{Slack}} + \sum_{k=1}^{N_{\mathrm{DG}}} P_{\mathrm{REDG}} = \sum_{i=1}^{N} P_{D,i} + \sum_{k=1}^{\mathrm{NB}} P_{\mathrm{Loss},k} \tag{17}$$

Inequality constraints

$$V_{\min} \le V_i \le V_{\max} \quad \text{where,} \quad V_{\min} = 0.95 \text{ p.u and } V_{\max} = 1.05 \text{ p.u} \tag{18}$$

$$S_k \le S_{k,\max} \quad \text{where,} \quad S_{k,\max} \text{ is maximum apperent power admissible for the branch} \tag{19}$$

$\sum_{k=1k=1}^{N_{\mathrm{AC}}} J_{K,\mathrm{AC}}^2 * R_K$ is power loss in AC micro-grid system, $\sum_{k=1}^{N_{\mathrm{DC}}} J_{K,\mathrm{DC}}^2 * R_K$ is power loss in DC micro-grid system, P_{REDG} is power injected by REDG units in DC micro-grid system, NB is number of branches in the system, N_{DG} is number of REDG units connected, N is number of buses in the system, i is bus number, k is branch number, $A_{\mathrm{PV}}, A_{\mathrm{FC}}$ are area required by PV and FC units, $n_{\mathrm{PV}}, n_{\mathrm{FC}}$ are the number of PV and FC units connected, $I_{\mathrm{PV}}, \eta_{\mathrm{PV}}, A_{\mathrm{PV}}$ are solar insolation (W/m^2), the efficiency of solar PV, the area required by PV unit (m^2) and $V_{\mathrm{FC}}, A_{\mathrm{FC}}, J$ are the output voltage of FC, area required by FC unit (m^2), current density (A/m^2), P_{Slack} is slack (substation) bus power, and P_D is the real power load connected at ith bus.

Butterfly optimization algorithm

Butterfly optimization is based on the ability of the butterflies to locate the source of fragrance accurately. They can also differentiate various fragrances and sense their intensities. In BO algorithm, butterflies are the searching agents. Fitness is correlated with the intensity of fragrance that can be generated by the butterfly. The movement of butterflies in search space will change its fitness. The sharing of information between butterflies is established through the propagation of fragrance. The searching ability of a butterfly depends on the sensing capability of the fragrance. This property will decide the movement of the butterfly towards a global search or local search (random). In BOA, the fragrance is formulated as a function of the physical intensity of stimulus as follows:

$$f = cI^a \tag{20}$$

where f is the perceived magnitude of the fragrance, i.e., fragrance receiving property by other butterflies, c is the sensory modality, I is the stimulus intensity, and a is the power exponent dependent on modality, which accounts the varying degree of absorption. Most of the cases $a\&c \in [0, 1]$. If $a = 1$, it means there is no absorption of fragrance, i.e., the amount of fragrance emitted by a particular butterfly is sensed in the same capacity by the other butterflies (fragrance propagation in an idealized environment). Thus, a butterfly emitting fragrance can be sensed from anywhere in the domain which in turn helps to reach the global optimum easily. On the other hand, if $a = 0$, it means that the fragrance emitted by any butterfly cannot be sensed by the other butterflies at all. Another important parameter $c \in [0, \infty]$ determines the convergence speed. The values of a and c crucially affect the convergence speed of the algorithm. For the maximization problem, the intensity can be proportional to the objective function [29].

In BO algorithm, the characteristics of butterflies are idealized as follows:

1. Every butterfly is supposed to emit some fragrance which enables the butterflies to attract each other (propagation of information).
2. Every butterfly will move randomly or toward the best butterfly emitting more fragrance.
3. The stimulus intensity of a butterfly is affected or determined by the topography of the objective function.

The detailed steps for implementation of BO algorithm are as follows.

Step 1: Initialize algorithm parameters such as the number of agents N, the dimension of the problem d, the maximum number of iterations $\text{Iter}_{\max}$, probability switch P, power exponent PE and sensor modality SM.

Step 2: Generate initial random solution x_i^j

$$x_i^j = x_{\min,j} + \left(x_{\max,j} - x_{\min,j}\right) * \text{rand}; \quad i = 1 : N \quad \text{and} \quad j = 1 : d \tag{21}$$

$$x = \begin{bmatrix} x_1^1 & x_1^2 & \cdots & x_1^{d-1} & x_1^d \\ x_2^1 & x_2^2 & \cdots & x_2^{d-1} & x_2^d \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ x_{N-1}^1 & x_{N-1}^2 & \cdots & x_{N-1}^{d-1} & x_{N-1}^d \\ x_N^1 & x_N^2 & \cdots & x_N^{d-1} & x_N^d \end{bmatrix} \tag{22}$$

where N is the number of agents and d is the number of decision variables,x_i^j represents the position of the ith agent in jth dimension generated randomly between the limits as $x_{\max,d}$ and $x_{\min,d}$ and rand() is a random number between 0 and 1.

$$\text{Case 1: } x_i^j = \left[A_{\text{PV}i}^{1,1}, A_{\text{FC}i}^{2,1} \cdots A_{\text{PV}i}^{j-1,k}, A_{\text{FC}i}^{j,k} \cdots A_{\text{PV}i}^{d-1,k}, A_{\text{FC}i}^{d,k}\right] \tag{23}$$

$$\text{Case 2: } x_i^j = \left[L_i^{1,1}, A_{\text{PV}i}^{2,1}, A_{\text{FC}i}^{3,1} \cdots L_i^{j-2,1}, A_{\text{PV}i}^{j-1,k}, A_{\text{FC}i}^{J,k} \cdots L_i^{d-2,1}, A_{\text{PV}i}^{d-1,k}, A_{\text{FC}i}^{d,k}\right] \tag{24}$$

where k = 1: N_{DCMG}, N_{DCMG} is number of DC micro-grids, L, A_{PV} and A_{FC} represents location of REDG, area of PV and area of FC, respectively.

Step 3: Evaluate the fitness (objective functions) of agents using Eq. 14. Record the *gbest* solution so far and set iteration count t as zero.

Step 4: Calculate the fragrance f_N for each agent or butterfly using Eq. 20.

Step 5: Perform a global search using Eq. 25 if rand < probability P *or* local search using Eq. 26 *if* $d > P$.

$$x_N^d(t+1) = x_N^d(t) + \left(r^2 * gbest - x_N^d(t)\right) * f_N \tag{25}$$

$$x_N^d(t+1) = x_N^d(t) + \left(r^2 * x_j^d(t) - x_k^d(t)\right) * f_N \tag{26}$$

where $x_j^d(t)$ and $x_k^d(t)$ are jth and kth butterflies from the solution space which belongs to the same swarm and r is a random number in [0, 1] and then Eq. 27 becomes a local random walk.

Step 6: Evaluate the fitness of each agent in the new population using Eq. 14.

Step 7: Update the *gbest* vector.

Compare each new solution with the previous solution, if the new solution is better than the previous solution, record the *gbest*; otherwise, discard the new solution and preserve the previous solution as it is.

Step 8: Stopping criterion.

If the maximum number of iterations has reached ($\text{iter}_{\max}$), computation is terminated. Otherwise, Step 4 to Step 7 are repeated.

The implementation flowchart for the BO algorithm is illustrated in Fig. 1.

Results and discussions

Standard radial distribution systems are modified as hybrid AC/DC micro-grid systems for the purpose of the study. The buses in the AC zone will have real and reactive power loads and lines will have resistance and reactance. But in DC zone buses will have only real power loads and lines will have only resistance. Based on the system topology, it

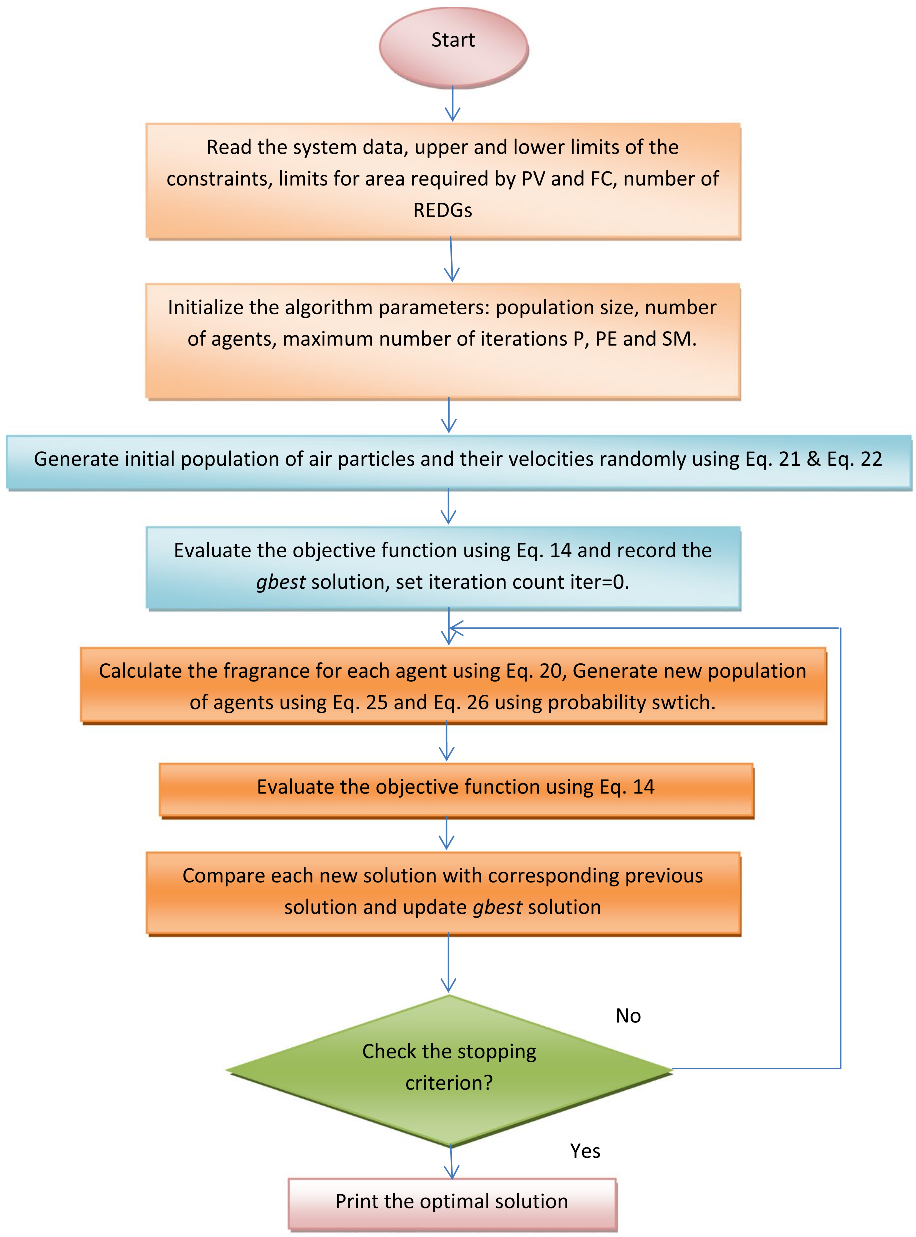

Fig. 1 Problem specific implementation flow chart of BO algorithm

was divided into several zones in which laterals and far end buses of the main feeder are considered as DC zones and they are separated with the help of HPCs (high-power converters) from the AC Zone or Main substation in this study. To calculate the system parameters like power losses, bus voltages, and line power flows, AC/DC Forward/Backward sweep load flow is used. Standard 33-bus, 69-bus [17] hybrid AC/DC distribution micro-grids systems are considered for the study. Hybrid AC/DC 33-bus micro-grid system is connected to a substation rated 100 MVA, 12.66 kV having a connected base load of 3715 kW and 840 kVAr, the base power loss of 139.77 kW and minimum voltage 0.9319 at 18th bus. For 69-bus system base power 100 MVA, base voltage 12.66 kV,

Table 1 Parameters description of BO algorithm

Parameter description	Assigned value
Population(pop)	150
Dimension(dim)	Case-1: number of DC micro-grids*2 (Area for FC and PV in each micro-grid)
	Case-2: number of DC micro-grids*3 (Location for REDG and area for PV REDG &FC REDG in each micro-grid)
Maximum number of iterations (*maxit*)	150
Modular modality 'c'	0.01
Power exponent 'a'	0.1–0.3
Probability switch 'P'	0.5

Table 2 Details of REDG units used in the study

REDG unit	Specification	Area required in m^2
PV	1 PV panel = 10 PV modules × 2.5 kW each = 25 kW	165
FC	1 FC array = 50 FC stacks × 0.5 kW each = 25 kW	10.5

base load 3801.89 kW and 766.6 kVAr, base case power loss 144.31 kW and minimum bus voltage are0.9318 at 65th bus. Note that all post performance numerical calculations presented in this work are based on reference [27] and uncertainty of REDG units are not considered to avoid complexity.

In order to demonstrate the effectiveness of the proposed approach for optimal allocation of REDG units in a hybrid AC/DC micro-grid system, it is applied to small- and medium-scale hypothetical 33- and 69-bus AC/DC hybrid distribution micro-grid systems. Tuned algorithm parameters of BO for the implementation are given in Table 1. The details of the REDG units used in this study are furnished in Table 2. All simulations are developed in MATLAB R2017a platform on Intel Core i5 2.7 GHz processor, 8 GB RAM. The optimal allocation of REDG units in a hybrid AC/DC micro-grid system is analyzed through two different cases.

Case 1: Optimal REDG units sizing at locations fixed by LRSF (Eq. 15 in [27]) using the BO algorithm without considering HPC losses.

Case 2: Simultaneous optimal allocation of REDG units using BO algorithm with and without considering HPC losses.

Optimal REDG unit allocation for 33-bus hybrid AC/DC micro-grid system

A hypothetical 33-bus hybrid AC/DC micro-grid system consists of three zones: Zone 1 is ACMG supported by substation and Zone 2, and 3 are DCMG supported by HPC and REDG units. The detailed 33-bus hybrid AC/DC micro-grid system is shown in Fig. 2. The maximum limit for area required by FC and PV REDG is taken as 3000 $m^2$and 500 m^2, respectively. The results obtained for the 33-bus hybrid AC/DC micro-grid system for two cases are given in Table 3. From Table 3, it is observed that the result obtained by BO is better than other results. In Case 1, i.e., without considering HPC losses, the lowest total area required by REDG units is 4537.2 m^2 with minimum system power loss

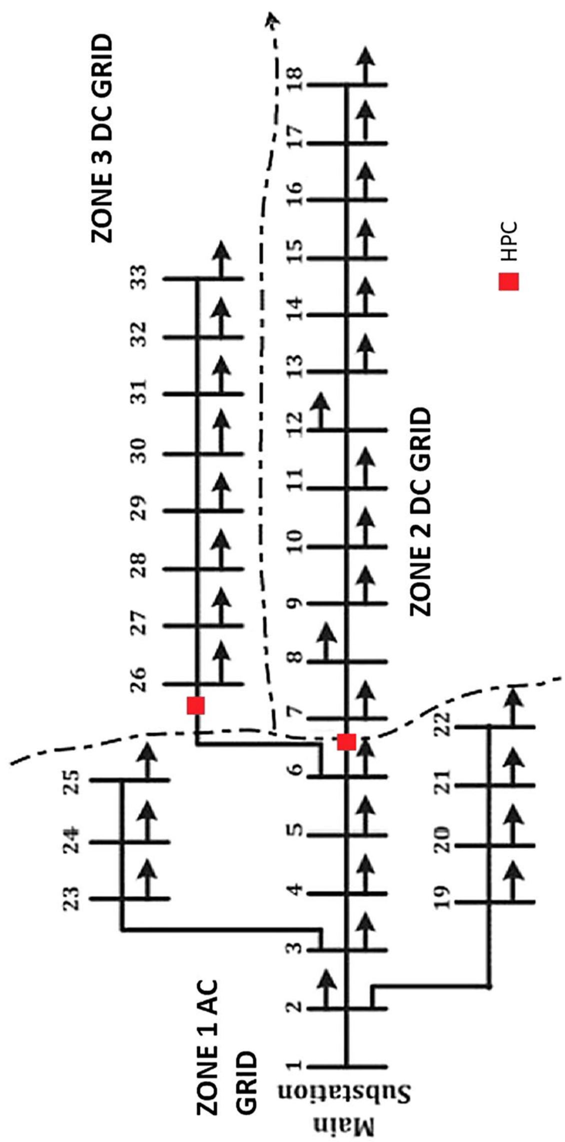

Fig. 2 Hypothetical 33-bus hybrid AC/DC distribution micro-grid system

Table 3 Summary of optimal allocation of REDG units in 33-bus AC/DC hybrid distribution micro-grid results with and without considering HPC losses

Parameter	Without HPC losses (WOHPCL)													With HPC losses (WHPCL)		
	Base Case	NM [27]		PSO [22]		CS [27]		HNMCS [27]		BOA CASE-1		BOA CASE-2		Base Case	BOA CASE-2	
		REDG@7	REDG@26	REDG@7	REDG@26	REDG@7	REDG@26	REDG@7	REDG@26	REDG@7	REDG@26	REDG@13	REDG@30		REDG@12	REDG@30
Solar-PV optimal area (m^2)		5278.56	1278.56	5000.83	4295.87	2747.71	4583.19	2191.53	2675.18	2332.7	1361	1678	1507.8		895.3438	664.5533
Solar-PV optimal power required (kW)		639.76	156.80	606.10	520.66	333.02	555.48	265.61	324.23	283	165	203	183		108.5157	80.5439
FC optimal area (m^2)		306.36	584.93	301.82	261.18	414.73	246.72	442.45	342.32	435.4	408.1	265.4	392.4		355.4116	395.3083
FC optimal power required (kW)		739.30	1416.20	730.74	632.34	1004.11	597.33	1071.22	828.81	1054	988	643	950		860.4901	957.0845
Total area required (m^2)		7462.57		9859.70		7992.35		5651.49		*4537.2*		*3843.6*			2310.6	
Total power loss (kW)	139.7	48.33		47.52		46.07		46.07		46.0532		*26.8325*		171.7	*27.3390*	
Power loss reduction (%)		65.45		66.0		67.0		67.07		67.05		80.80				
Convergence time (s)		1.06		12.61		9.22		8.86		7.05		8.27			7.14	8.54
Number of PV panels		320	77	303	260	167	278	133	163	142	83	102	92		54	40
Number of FC		29	56	29	25	39	23	43	33	42	39	26	38		34	38

Italics values are represents better values

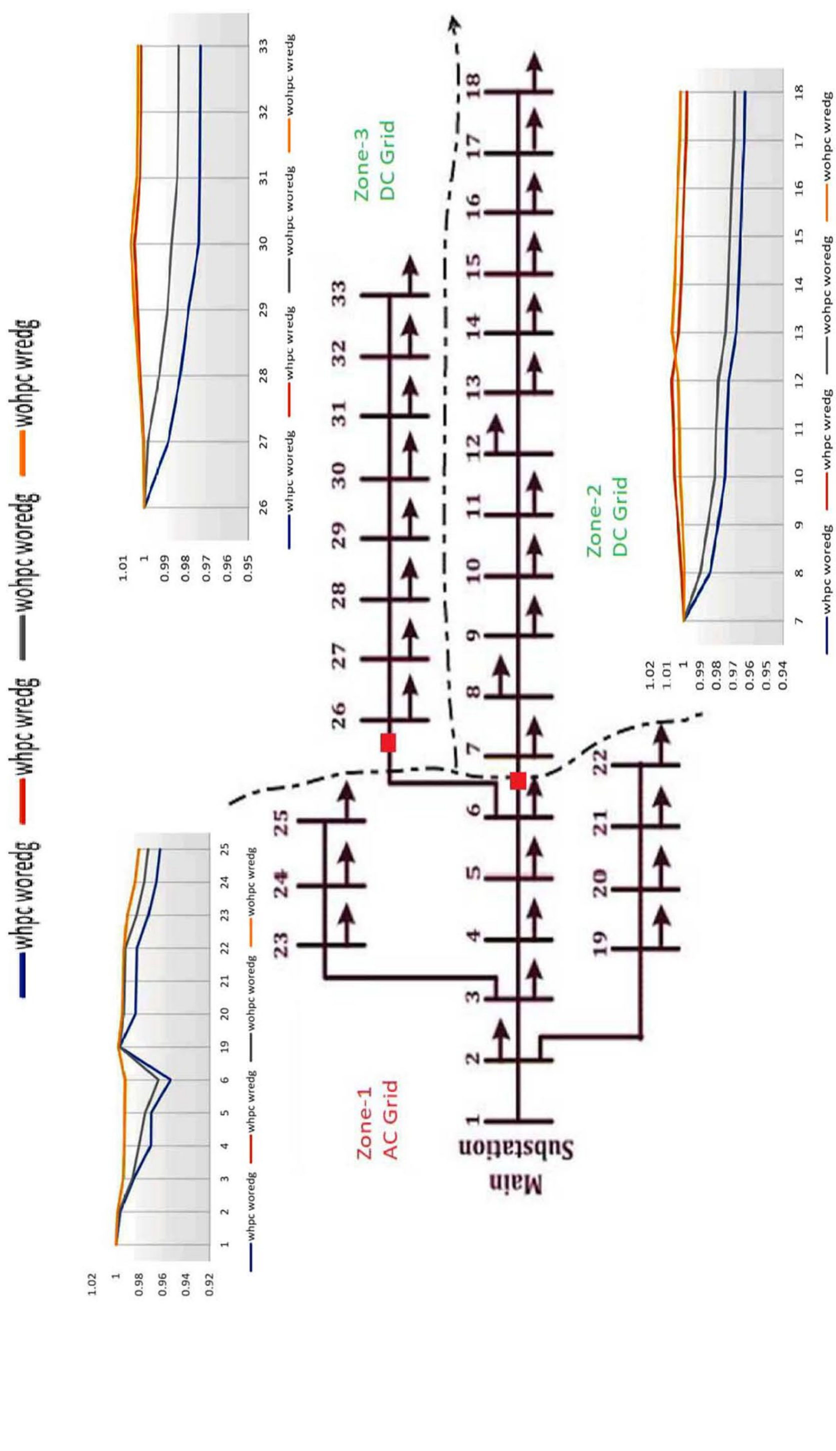

Fig. 3 Zone-wise voltage profile of 33-bus hybrid AC/DC distribution micro-grid for different cases

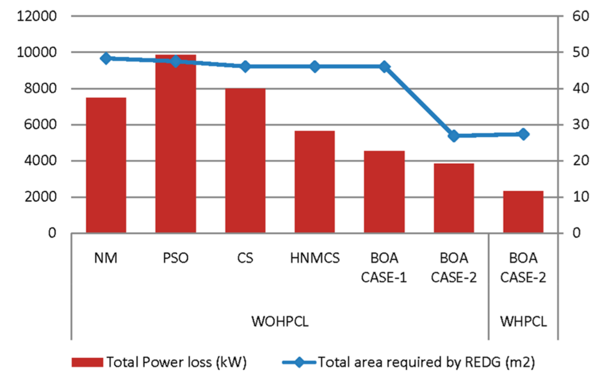

Fig. 4 Comparison of power loss vs operational area required by REDG units for various optimization algorithms for 33-bus hybrid AC/DC distribution micro-grid

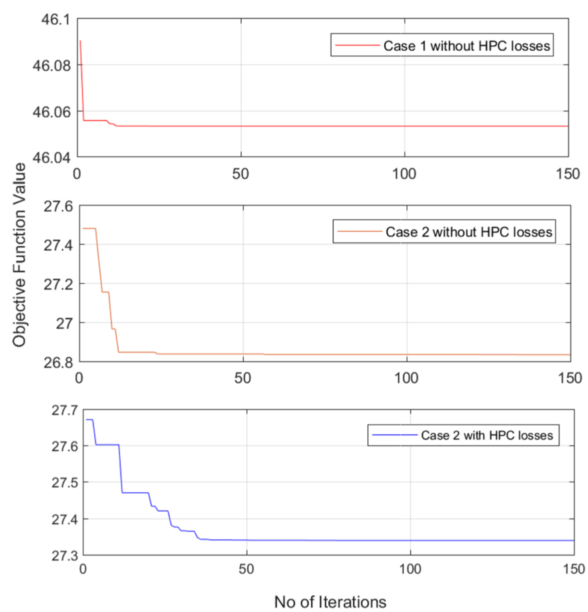

Fig. 5 Case-wise convergence characteristics obtained by BO algorithm for 33-bus hybrid AC/DC distribution micro-grid

of 46.05 kW and the total power loss reduction is 67.05%. The optimal power required by PV is 283 kW and FC is 1054 kW at 7th bus with 142 PV panels and 42 FC arrays. Similarly, the optimal power required by PV is 165 kW and FC is 988 kW on 26th bus with 83 PV panels and 39 FC arrays. However, the results obtained by BO in Case 2 are quite interesting and encouraging. The total area required by REDG units is 3843.6 m^2 with minimum system power loss of 26.83 kW, and the total power loss reduction is 80.8%. The optimal power required by PV is 203 kW and FC is 643 kW at 13th bus with 102 PV panels and 26 FC arrays. Similarly, the optimal power required by PV is 183 kW and FC is 950 kW on 30th bus with 92 PV panels and 38 FC arrays. It is observed that

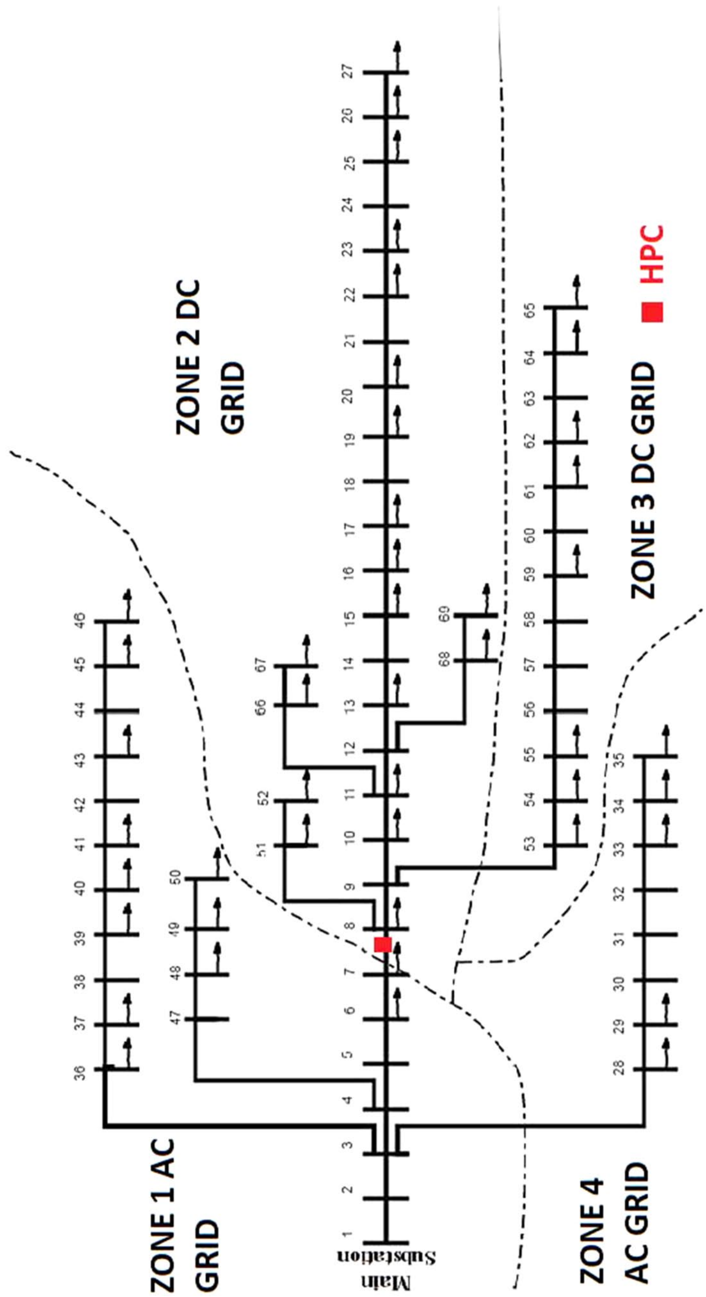

Fig. 6 Hypothetical 69-bus hybrid AC/DC distribution micro-grid system

Table 4 Comparison of energy flow in 33-bus AC/DC hybrid distribution Micro-grid under standalone mode of REDG

Zone (grid type)	Zone 1 (AC grid)		Zone 2 (DC grid)		Zone 3 (DC grid)	
Method	MNMCS	BOA	MNMCS	BOA	MNMCS	BOA
Total load (kWh)	41,280	41,280	25,800	25,800	22,080	22,080
REDG energy generated (kWh)	–	-	32,043.6	32,088	27,468	27,192
Excess energy to AC grid (kWh)	–	-	8200.56	6288	5123.28	5112
Substation energy (kWh)	31,826.16	30,528	–	-	–	-
Minimum voltage @ bus (p.u)	0.9823 @25	0.9831 @25	0.9706 @18	1.0000 @7	0.9840 @33	1.0000 @26
Maximum voltage @ bus (p.u)	1.0000 @1	1.0000 @1	1.0000 @7	1.0056 @14	1.0000 @26	1.0063 @30
Energy loss (kWh)	1085.52	648				
Loss reduction	67.64%	80%				
Coal consumption (ton)	22.28	19.36				
CO2 emission (ton)	18.97	16.19				
Energy-saving from substation	65.60%	67.58%				

the reduction in system power losses is significant in Case 2. The reason is in Case 1 the REDG unit locations are predetermined by the LRSF method and then optimal sizes are calculated at those fixed locations. But in Case 2, REDG unit's locations and respective sizes are determined simultaneously. It is also observed that the base case power loss is 171.7 kW (including HPC losses). The optimal power required by PV is 108.5 kW and FC is 860.4 kW at 12th bus with 54 PV panels and 34 FC arrays. Similarly, the optimal power required by PV is 80.5 kW and FC is 957 kW at 30th bus with 40 PV panels and 38 FC arrays obtained by BO for Case 2.

A detailed comparison of the area required by REDG units versus total power losses of the system by various optimization algorithms is presented in Fig. 3. From Fig. 4, it is clear that in both cases the BO algorithm performed better than other algorithms. Another significant benefit of the REDG unit's optimal allocation in hybrid AC/DC micro-grid is voltage profile improvement which is shown in Fig. 4. From Fig. 6, it is observed that the bus voltage profile has been improved in all three zones of the system for both cases with and without considering HPC losses. Convergence characteristics of the BO algorithm for the minimization of the desired objective function for different cases are given in Fig. 5. From Fig. 6, it is understood that the BO algorithm reached the final solution with good convergence i.e., 13th iteration for Case 1 without HPC losses, at 57th iteration for Case 2 without HPC losses and at 36th iteration for Case 2 with HPC losses. It is identified that the energy supplied through substation is 92514.38 kWh, the amount of coal consumed is 64.76 ton, and CO_2 emission into the atmosphere is 55.14 ton without the integration of REDG units into the system. Energy flow results of the system under REDG units standalone mode of operation are presented in Table 4. From Table 4, it is clear that the proposed approach can improve the power loss reduction percentage, i.e., with HNMCS its value is 67% and with BO is 80%. Energy-saving from the substation is improved from 65 to 67%, coal consumption is reduced from 22 to 19 tons that intern reduced the CO_2 emission from 18.9 tons to 16 tons. And it is also observed that integrated REDG units under the standalone mode of operation in Zone 2 and 3 (DC grid) are producing sufficient

Table 5 Optimal allocation of REDG units in 69-bus AC/DC hybrid distribution micro-grid using BO algorithm with and without considering HPC losses

Parameter	**Without HPC losses**							**With HPC losses**			
	Base case	**BOA CASE-1**			**BOA CASE-2**			**Base case**	**BOA CASE-2**		
		REDG@8	**REDG@28**	**REDG@61**	**REDG@18**	**REDG@61**	**REDG@54**		**REDG@19**	**REDG@61**	**REDG@54**
Solar-PV optimal area (m^2)		126.04	64.82	26.72	31.971	66.276	199.81		56.83	196.46	36.011
Solar-PV optimal power required (kW)		15	8	3	3.8749	8.0326	24.217		6.8886	23.811	4.3645
FC optimal area (m^2)		419.95	114.24	683.79	194.47	675.02	176.65		208.7	667.21	136.6
FC optimal power required (kW)		1017	277	1656	470.83	1634.3	427.68		505.28	1615.4	330.72
Total area required (m^2)		1361.8			1344.2				1301.8		
Total power loss (kW)	144.31	11.5074			4.658			227.4	5.5461		
Power loss reduction (%)		92.05			98.2				97.55		
Number of PV panels		8	4	2	8	4	2		4	12	3
Number of FC		40	11	66	40	11	66		20	64	13

Table 6 Comparison of results obtained for 69-bus AC/DC hybrid distribution micro-grid by various optimization algorithms

Parameter	NM [27]	PSO [22]	CS [27]	HNMCS [27]	BOA CASE-1	BOA CASE-2
Total area required by REDG (m^2)	2264.72	7334.53	2885.18	1363.88	**1361.8**	*1344.2*
Total power loss (kW)	11.63	11.52	11.52	11.52	*11.5074*	*4.658*
Power loss reduction (%)	91.94	92.0	92.0	92.0	*92.05*	*98.2*
Convergence time (s)	2.42	30.45	21.68	19.13	15.43	17.21

Italis values are represents better values

energy to cater to the needs of AC grid without any shortfall and excess energy is useful to support the AC grid.

Optimal REDG unit allocation for 69-bus hybrid AC/DC micro-grid system

69-bus hybrid AC/DC micro-grid system consists of three zones: Zone 1 is ACMG supported by substation and Zone 2, Zone3 and Zone 4 are DCMG supported by HPC and REDG units. The detailed 69-bus hybrid AC/DC micro-grid system is shown in Fig. 6. The maximum limit for area required by FC and PV REDG is taken as 500 m^2 and 800 m^2, respectively. Numerical outcomes obtained by case-wise based on BO algorithm for 69-b*us hybrid AC/DC micro-grid system are in Table 5. And a comparison of outcomes based on various algorithms is furnished in Table 6. From Table 6, it is observed in Case 1, i.e., without considering HPC losses the lowest total area required by REDG units is 1361.84 m^2 with minimum system power loss of 11.50 kW and the total power loss reduction is 92%. The optimal power required by PV is 15 kW and FC is 1017 kW at 8th bus with 8 PV panels and 40 FC arrays. Similarly, the optimal power required by PV is 8 kW and FC is 277 kW at 28th bus with 4 PV panels and 11 FC arrays and power required by PV is 3 kW and FC is 1656 kW at 61st bus with 2 PV panels and 66 FC arrays. However, the results obtained by BO and HNMCS are almost the same. But the results obtained by BO in Case 2 are surprising. The total area required by REDG units is 1344.2 m^2 with minimum system power loss of 4.65 kW and the total power loss reduction is 98.2%. Optimal locations obtained for the integration of REDG units are 18, 61 and 54 buses. The optimal power produced by PV and FC at these locations is 3.8 kW, 8.03 kW, 24.21 kW, and 470.8 kW, 163.8 kW, and 427.6 kW, respectively. It is observed that the reduction in system power losses is significant in Case 2. The reason is in Case 1, the algorithm does not have the flexibility to choose the optimal locations because they are fixed based on LRSF. At those fixed locations algorithm has to find the best suitable size of REDG units. But, in Case 2 the algorithm has the freedom to choose optimal locations as well as optimal sizes simultaneously. It is worth noting point that the proper size of REDG units at proper locations always guarantees the better performance of the system. It is also observed that the base case power loss is 227.4 kW (including HPC losses). The total area required and power produced by REDG units is 1301 m^2 and 2486.2 kW, respectively. The optimal locations are 19, 61 and 54 buses. In this case, the system power loss is increased from 144 to 227 kW. The reason is power loss due to HPC's will alter the power flow in the respective feeder, and as a result, the change in branch currents may increase the feeder losses.

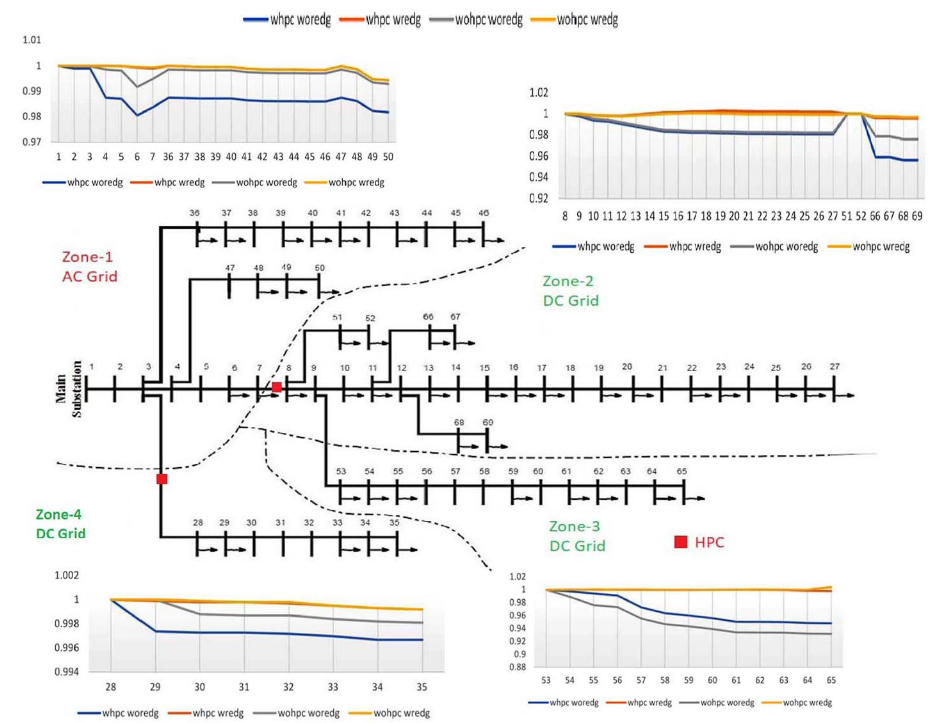

Fig. 7 Zone-wise voltage profile of 69-bus hybrid AC/DC distribution micro-grid for different cases

A detailed comparison of the area required by REDG units versus total power losses of the system by various optimization algorithms is presented in Fig. 7. From Fig. 8, it is clear that in both cases the BO algorithm performed better than other algorithms. Another significant benefit of REDG unit's optimal allocation in hybrid AC/DC micro-grid is voltage profile improvement which is shown in Fig. 8. From Fig. 9, it is observed that the bus voltage profile has been improved in all three zones of the system for both cases with and without considering HPC losses. Convergence characteristics of the BO algorithm for the minimization of the desired objective function for different cases are given in Fig. 9. From Fig. 9, it is understood that the BO algorithm reached the final solution with smooth convergence. It is identified that the energy supplied through substation is 25848 kWh, the amount of coal consumed is 12.07 ton, and CO_2 emission into the atmosphere is 10.2 ton without the integration of REDG units into the system. Energy flow results of the system with REDG unit's standalone mode of operation are presented in Table 7. From Table 7, it is clear that the proposed approach can improve the power loss reduction percentage i.e., with HNMCS its value is 90.1% and with BO is 97.5%. Energy-saving from the substation is improved from 76 to 80%, coal consumption is reduced from 15.5 to 12 ton that intern reduced the CO_2 emission from 13.2 to 10.2 ton. And it is also observed that integrated REDG units under the standalone mode of operation in Zone 4 (DC grid) are producing excess, i.e., 8601 kWh, energy which is not sufficient to cater the needs of Zone 1 (AC grid), Zones 2 and 3 (DC Grid) and hence it requires load shedding or additional REDG support from other DC grids or through the substation to satisfy the demand.

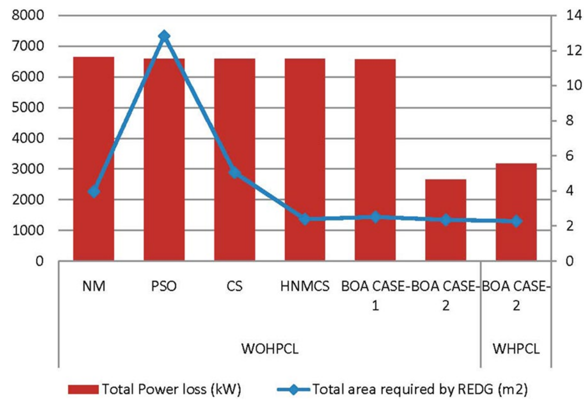

Fig. 8 Comparison of power loss vs operational area required by REDG units for various optimization algorithms for 69-bus hybrid AC/DC distribution micro-grid

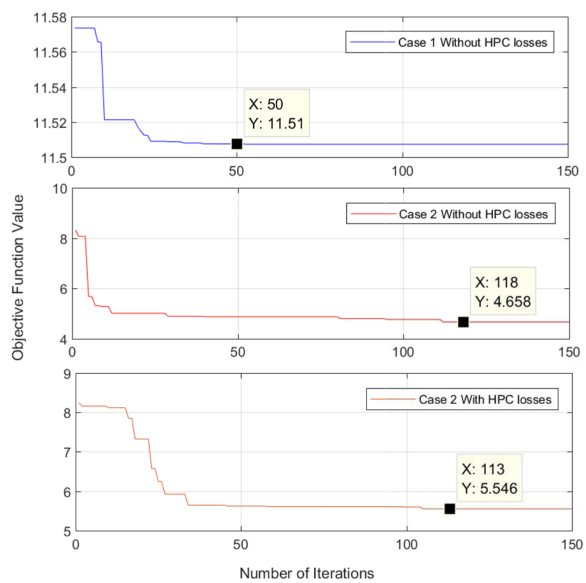

Fig. 9 Case-wise convergence characteristics obtained by BO algorithm for 69-bus hybrid AC/DC distribution micro-grid

Since BOA is a heuristic search method, its outcome may have certain randomness. In this work, it has been handled carefully by proper selection of decision variable limits. So, BO algorithm is tested by running 100 times for each case. Further, the computational complexity of the proposed BOA is analyzed by popular statistical methods such as Friedman and Quade test. The obtained ranks by BOA are compared with existing results available in the literature and also furnished in Table 8. From Table 8, it is observed that solution-quality and robustness-wise BOA is almost closer to HNMCS. However, HNMCS proves to be better than other algorithms in the race due to its hybrid nature.

Table 7 Comparison of energy flow in 69-bus AC/DC hybrid distribution micro-grid under standalone mode of REDG

Zone (grid type)	Zone 1 (AC grid)		Zone 2 (DC grid)		Zone 3 (DC grid)		Zone 4 (DC grid)	
Method	**HNMCS**	**BOA**	**HNMCS**	**BOA**	**HNMCS**	**BOA**	**HNMCS**	**BOA**
Total load (kWh)	25,848.96	25,848.96	21,998.4	21,998.4	41,202	41,202	2196	2196
REDG energy generated (kWh)	–		24,850.8	11,392	39,769.68	39,408	6852.24	10,824
Excess energy to AC grid (kWh)	–		2592.48	–	–	–	4655.52	8601
Substation energy (kWh)	20,693.04	17,227.32	–		1452.96		–	
Minimum voltage @ bus (p.u)	0.9942 @50	0.9943 @50	0.9996 @52	0.9969 @68	0.9970 @53	1.0000 @53	0.9992 @35	0.9992 @35
Maximum voltage @ bus (p.u)	1.0000 @1	1.0000 @1, 36	1.0169 @15	1.0009 @17	1.0000 @61	1.0005 @62	1.0000 @28	1.0000 @28
Energy loss (kWh)	341.04	112						
Loss reduction %	90.15	97.55						
Coal consumption (ton)	15.5	12.07						
CO_2 emission (ton)	13.2	10.21						
Energy-saving from substation	76.61%	80.54%						

Table 8 Statistical analysis of results

Type	Method	Friedman test	Quade test
33-Bus AC/DC hybrid MG	NM	2.75	2.82
	PSO	2.28	2.2
	CS	3.96	3.97
	HNMCS	1	1
	BOA	1.17	1.32
69-Bus AC/DC hybrid MG	NM	2.61	2.69
	PSO	2.09	2.01
	CS	3.47	3.84
	HNMCS	1	0.99
	BOA	1.28	1.47

Conclusions

In this paper, an efficient approach was proposed for optimal integration of REDG units in hybrid AC/DC distribution micro-grids to maximize the technical benefits of the system with minimum operational area required by REDG units. Optimal locations and sizes for REDG units are determined simultaneously using a butterfly optimizer which is proved as a better approach by obtained results. It is identified that additional REDG units are required in DC zones of the 69-bus system to produce the energy to satisfy the present demand. The proposed approach is an efficient technical tool for achieving better results in an optimal allocation of REDG units in hybrid AC/DC distribution micro-grids. The future scope of this work is to include economic and technical benefits of

REDG units with uncertainties, effects of probabilistic load models (daily load pattern) and PEV loads with different charging scenarios using Pareto optimal approach.

Abbreviations

$P_{\mathrm{Li,AC}}$: Active power demand of the *i*th AC bus; $Q_{\mathrm{Li,AC}}$: Reactive power demand of the *i*th AC bus; $I_{i,\mathrm{AC}}$: Bus current of a *j*th bus in AC grid; N_{AC}: Number of AC buses; $J_{k,\mathrm{AC}}$: Branch current of a *j*th branch in AC grid; BIBC: Bus injected Brach current matrix; BCBV: Brach current to bus voltage matrix; $V_{i,\mathrm{AC}}$: Voltage of an *i*th AC bus; V_0: Reference voltage of the buses; $V_{i,\mathrm{AC}}^{\mathrm{iter}}$: Voltage of an *i*th AC bus during iteration; ε: Tolerance value; $P_{\mathrm{Li,DCeff}}$: Effective active power demand of an *i*th DC bus; $V_{i,\mathrm{DC}}$: Voltage of an *i*th DC bus; $I_{i,\mathrm{DC}}$: Bus current of a *j*th bus in DC grid; $P_{\mathrm{Li,DC}}$: Active power demand of the *i*th DC bus; P_{REDG}: Active power supplied by REDG; $J_{k,\mathrm{DC}}$: Branch current of a *j*th branch in DC grid; $V_{i,\mathrm{DC}}$: Voltage of an *i*th DC bus; $V_{i,\mathrm{AC}}^{\mathrm{iter}}$: Voltage of an *i*th DC bus during iteration; P_{AC}: Active power observed by the convertor from the AC grid; Q_{AC}: Reactive power observed by the convertor from the AC grid; I_{DC}: Current on the DC side of the convertor; V_{DC}: Voltage on DC side of the convertor; $P_{C,\mathrm{Loss}}$: Power lost in the convertor; *R*: Resistance offered by the HPC; X_{HPC}: Equivalent reactance of the convertor; $P_{C,\mathrm{Loss}}$: Power loss in the convertor; R_K: Resistance of the *k*th branch; n_{PV}: Efficiency of the PV panel; I_{PV}: Output current of PV panel; V_{PV}: Output voltage of PV panel; A_{PV}: Area required by PV unit; n_{FC}: Efficiency of the PV panel; V_{FC}: Output voltage of FC panel; A_{FC}: Area required by FC unit; J: Current density of FC unit; P_{Slack}: Slack Bus power.

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References

1. Pecas Lopes JA, Moreira CL, Madureira AG (2008) Defining control strategies for analysing microgrids islanded operation. IEEE Trans Power Syst 21(2):1–7
2. Guerrero JM, Vasquez JC, Matas J, De Vicuña LG, Castilla M (2011) Hierarchical control of droop-controlled AC and DC microgrids: a general approach toward standardization. IEEE Trans Ind Electron 58(1):158–172
3. Hamad AA, Azzouz MA, El Saadany EF (2016) A sequential power flow algorithm for islanded hybrid AC/DC microgrids. IEEE Trans Power Syst 31(5):3961–3970
4. Kim JO, Nam SW, Park SK, Singh C (1998) Dispersed generation planning using improved Hereford ranch algorithm. Electr Power Syst Res 47(1):47–55
5. Borges CLT, Falcão DM (2006) Optimal distributed generation allocation for reliability, losses, and voltage improvement. Int J Electr Power Energy Syst 28(6):413–420
6. Singh RK, Goswami SK (2009) Optimum siting and sizing of distributed generations in radial and networked systems. Electr Power Compon Syst 37(2):127–145
7. Singh D, Singh D, Verma KS (2009) Multiobjective optimization for DG planning with load models. IEEE Trans Power Syst 24(1):427–436
8. Shukla TN, Singh SP, Srinivasarao V, Naik KB (2010) Optimal sizing of distributed generation placed on radial distribution systems. Electr Power Compon Syst 38(3):260–274
9. Singh RK, Goswami SK (2011) Multi-objective optimization of distributed generation planning using impact indices and trade-off technique. Electr Power Compon Syst 39(11):1175–1190
10. Novoa C, Jin T (2011) Reliability centered planning for distributed generation considering wind power volatility. Electr Power Syst Res 81(8):1654–1661
11. Moradi MH, Abedini M (2012) A combination of genetic algorithm and particle swarm optimization for optimal distributed generation location and sizing in distribution systems with fuzzy optimal theory. Int J Green Energy 9(7):641–660
12. El-Zonkoly AM (2011) Optimal placement of multi-distributed generation units including different load models using particle swarm optimisation. IET Gener Transm Distrib 5(7):760
13. Wang L, Singh C (2008) Reliability-constrained optimum placement of reclosers and distributed generators in distribution networks using an ant colony system algorithm. IEEE Trans Syst Man Cybern Part C Appl Rev 38(6):757–764

14. Abu-Mouti FS, El-Hawary ME (2011) Optimal distributed generation allocation and sizing in distribution systems via artificial bee colony algorithm. Power Deliv IEEE Trans 26(4):2090–2101
15. Arya LD, Koshti A, Choube SC (2012) Distributed generation planning using differential evolution accounting voltage stability consideration. Int J Electr Power Energy Syst 42(1):196–207
16. Rao RS, Ravindra K, Satish K, Narasimham SVL (2013) Power loss minimization in distribution system using network reconfiguration in the presence of distributed generation. IEEE Trans Power Syst 28(1):317–325
17. Injeti SK, Prema Kumar N (2013) A novel approach to identify optimal access point and capacity of multiple DGs in a small, medium and large scale radial distribution systems. Int J Electr Power Energy Syst 45(1):142–151
18. Kumar Injeti S, Shareef SM, Kumar TV (2018) Optimal allocation of DGs and capacitor banks in radial distribution systems. Distrib Gener Altern Energy J 33(3):6–34
19. Injeti SK (2016) A Pareto optimal approach for allocation of distributed generators in radial distribution systems using improved differential search algorithm. J Electr Syst Inf Technol 5:908–927
20. Murthy VVSN, Kumar A (2013) Comparison of optimal DG allocation methods in radial distribution systems based on sensitivity approaches. Int J Electr Power Energy Syst 53(1):450–467
21. Singh AK, Parida SK (2016) Novel sensitivity factors for DG placement based on loss reduction and voltage improvement. Int J Electr Power Energy Syst 74:453–456
22. Devi S, Geethanjali M (2014) Optimal location and sizing determination of distributed generation and DSTATCOM using particle swarm optimization algorithm. Int J Electr Power Energy Syst 62:562–570
23. Injeti SK, Kumar TV (2018) A WDO framework for optimal deployment of DGs and DSCs in a radial distribution system under daily load pattern to improve techno-economic benefits. Int J Energy Optim Eng 7(2):1–38
24. Melgar-Dominguez OD, Pourakbari-Kasmaei M, Mantovani JRS (2019) Adaptive robust short-term planning of electrical distribution systems considering siting and sizing of renewable energy based DG units. IEEE Trans Sustain Energy 10(1):158–169
25. Zeng B, Wen J, Shi J, Zhang J, Zhang Y (2016) A multi-level approach to active distribution system planning for efficient renewable energy harvesting in a deregulated environment. Energy 96:614–624
26. Bharothu JN, Sridhar M, Rao RS (2018) Modified adaptive differential evolution based optimal operation and security of AC-DC microgrid systems. Int J Electr Power Energy Syst 103(January):185–202
27. Senthil Kumar J, Charles Raja S, Jeslin Drusila Nesamalar J, Venkatesh P (2018) Optimizing renewable based generations in AC/DC microgrid system using hybrid Nelder–Mead–Cuckoo search algorithm. Energy 158:204–215
28. Bahrami S, Wong VWS, Jatskevich J (2015) Optimal power flow for AC-DC networks. In: 2014 IEEE international conference on smart grid communication. SmartGridComm 2014, pp 49–54
29. Arora S, Singh S (2018) Butterfly optimization algorithm : a novel approach for global optimization. Soft Comput 23:715–734

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