Renewable Energy 99 (2016) 315–324

Contents lists available at ScienceDirect

Renewable Energy

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Optimal operation of autonomous microgrid including wind turbines

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ARTICLE INFO

Article history:
Received 13 March 2016
Received in revised form
27 May 2016
Accepted 5 July 2016

Keywords:
Microgrid
Renewable energy resources
Multi-objectives
Wind generation
Gas prices

ABSTRACT

This paper gives a novel hybrid optimization method to find optimal sitting and operation of an autonomous MG at the same time. The operation is optimized via finding the optimal droop gain parameters of DGs. The optimization problem is formulated as a multi-objective problem where the objectives are applied to minimize the fuel consumption of DGs and to improve the voltage profile and stability of MG subject to operational and security constraints. A hybrid algorithm, named HS-GA, is developed to solve the paper optimization problem. A new formulation of power flow is derived to run the proposed algorithm where the steady state frequency of system, reference frequency, reference voltage and droop coefficients of DGs, based on a droop controller, are considered as optimization variables. The performance of the paper approach is compared with other optimization and non-optimization methods in MG with 33and 69 buses using MATLAB. The performance of the proposed method is compared with a method that the parameters of DGs are pre-determined without conducting any optimization process. The results show, which optimized droop parameters improves the operation of the MG.

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1. Introduction

Distributed generations (DG) emerge from the utilization of renewable energy resources (RES) in distribution networks. DGs come in different types, controllable such as diesel generators, fuel cells and micro-turbines, and uncontrollable such as wind turbines and photovoltaic systems. DGs along with energy storages, controllers, loads, and communication systems make a small low-voltage system, known as a Micro-grid (MG), which is a significant and essential part of distribution networks development [1]. MGs operate in two different modes, namely connected where MG is connected to a grid via the point of common coupling (PCC), and autonomous, also known as islanded mode. Among different factors influencing the behavior of MGs, finding optimal sizing, siting and operation of DGs are of particular interests in the power grid optimization literature [2–7]. To find the optimal operation of the autonomous MG with and without droop control the use of central controller is vital. A number of methods exist concerning the improvement of the operation of the autonomous MG with central controller (MGCC). In Ref. [8] optimum scheduling techniques for autonomous MGs are discussed focusing on economic profits. In Refs. [9] and [10], MGCC is utilized to optimize the total fuel cost of islanded MG where DGs are modeled based on droop control and a combined heat and power (CHP) unit as well as a heat load in the MG are used. The research of [11] looks at the power dispatch among DGs using an evolutionary algorithm. In Refs. [12] and [13], different techniques are proposed to reduce fuel cost of islanded MGs. In Refs. [14] and [15], an analytical programming method is given for sharing reactive power among DGs using DGs droop control and considering uncertainty of small wind plants. An optimum combination of DG is developed in Refs. [16], [17] and [18]. In Refs. [23], [32–35] operation of DGs is optimized subject to environmental constraints. In the authors, previous studies [24] and [25] optimal sizing and operational strategy of DGs in MGs was proposed using a hybrid evolutionary algorithm by considering the grid-connected mode of MGs [29].

Despite the great contribution of the above studies in the area of power grid optimization, a review of the literature reveals that few studies have looked at both optimal operation and location of DGs. This paper addresses this shortfall. It gives a novel optimization approach to find the optimal location and operation of an autonomous MG at the same time. The operation is optimized via finding the optimal droop gain parameters of DGs. The optimization

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http://dx.doi.org/10.1016/j.renene.2016.07.008
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problem is formulated in terms of a multi-objective problem to minimize the fuel consumption of DGs and to improve the voltage profile and stability of MG subject to operational and security constraints. To propose the paper optimization method, the harmonic search, HS, algorithm is adopted. Although HS is regarded as one popular optimization approach it has some deficiency due to its low speed divergence and sticking in local optimal solutions. To cope with such deficiency HS is combined genetic algorithm, GA, to provide a new optimization algorithm. A new load flow formulation is derived to run the proposed algorithm where the steady state frequency of system, reference frequency, reference voltage and droop coefficients of DGs, based on a droop controller, are the optimization variables. In the paper proposed approach, first the Pareto front of non-dominated results is provided then, the best solution of non-dominated results is obtained by employing a fuzzy method.

The paper is structured as follows. First, a background to the paper is discussed. Then the problem formulation is developed and its corresponding solution is given. This is followed by providing numerical results and discussion.

2. Background

In order to give some background on the paper three issues are argued here. Two modes of operation can be considered for MGs, namely the grid-connected mode and the autonomous mode. In a grid-connected mode, voltage and frequency of MG are dictated by grid where MG controls the electrical power interchange with grid [19].

In the autonomous mode where there is no link between MG and the main grid, the MG control is responsible for frequency and voltage regulation. Also, the power generated by MG needs to meet its local demand. To share power among DGs a proper control method is required to manage the supply of MG's load. There are two control methods: centralized and decentralized control. Centralized control methods require remarkable data transfer capacity and reliable communication link to swap power division signals among DGs [20] and [21]. Though, such methods are costly due to the use of high bandwidth and reliable communication links. The centralized control method is appropriate for small-scale MGs where DG units are close together. With a decentralized method, load demand is shared between DGs using droop controller characteristics and local measurement (frequency and voltage variations). The decentralized method provides a proper voltage regulation in PCC, though there are some drawbacks regarding decentralized methods such as voltage drop in some buses, lack of minimizing power generation costs of MG and lack of dispatching reactive power generation among DGs (based on DG characteristics) [22]. To cope with these drawbacks, tuning of DGS droop parameters becomes of particular importance. In practice MGCC might be employed to make such parameters tuning.

In this paper, a combination of MGCC and a decentralized control method is developed to solve the optimal power sharing problem of DGs. MGCC is employed to provide optimum DGs droop parameters while the decentralized controller is used to operate with optimal droop parameters. The merit of this combination is that MG acts based on the decentralized control in the environment where the likelihood of having problems related to MGCC or communication link is high. Accordingly, any MG defeat is prevented and all DGs can keep operating though such operation is not optimal. Another merit is reliability and low cost of decentralized methods with droop control compared with conventional methods due to reducing communication bandwidth and making the control system robust against any communication link defect.

3. Problem formulation

The problem here is to find DGs location and static characteristics of DGs to optimize three objective functions comprising fuel cost reduction of DG units (f_1); voltage stability improvement (f_2); and reducing the total voltage variation (f_3). These three objective functions are mathematically formulated as a minimization problem as follow,

$$Min\ \{f_1(i,k),\ f_2(i,k),\ f_3(i,k)\} \tag{1}$$

where i is the bus number, representing DGs location; and k represents static characteristics, including frequency, voltage references and static droop gains,

$$k = \left\{\omega_i^*,\ \left|V_i^*\right|,\ s_{pi},\ s_{qi}\right\} \quad i \in N_{dr} \tag{2}$$

A. Fuel cost of DG units

Fuel consumption cost can mathematically be given by

$$f_1 = \sum_{i=1}^{n_{DG}} P_{DG_i} * C_i(P_{DGi}) \tag{3}$$

C_i (P_{DGi}) is the fuel consumption of the ith DG unit as a function of its active power generation. It should be noted that the DG units based on gas turbines and synchronous generators.

B. Voltage Stability Index (VSI)

This index can mathematically be given by, [25],

$$VSI(i+1) = V_i^4 - 4\left[\hat{P}_{i+1}X_i - \hat{Q}_{i+1}R_i\right]^2 - 4\left[\hat{P}_{i+1}R_i + \hat{Q}_{i+1}X_i\right]^2 V_i^2. \tag{4}$$

VSI is utilized to compute the stability of a MG line as illustrated in Fig. 1. For the stable action of MG, the VSI should be positive in microgrid buses. Then, to locate DG units the bus with the lowest VSI must be chosen as the voltage of such bus is more probable to be instable. The second objective function is to improve VSI which is equivalent to maximizing (4) or minimizing f_2 as given by,

$$f_2 = \frac{1}{VSI(i+1)} \quad i = 1, 2, \ldots, NB\,. \tag{5}$$

C. Total Voltage Variation (TVV)

Total voltage variation (TVV) is used as the third objective function. This can be mathematically expressed by Ref. [31]

$$f_3 = \frac{\sum_{i=1}^{NB}|1 - V_i|}{NB} \tag{6}$$

By minimizing (6), a flatter voltage profile can be obtained leading

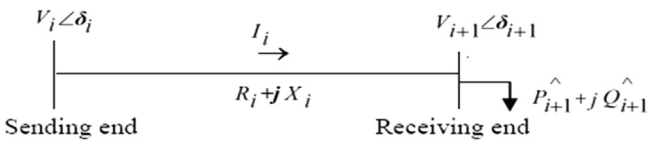


Fig. 1. One-line diagram of the MG line.

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to a reduction in voltage variation in MG.

D. Constraints

Two types of constrains exist in the optimization problem as outlined below.

Equality constraints are nonlinear power flow equations which can be obtained by Refs. [6],

$$P_{gi} = P_i + V_i \sum_{j=1}^{NB} V_j Y_{ij} \cos(\delta_i - \delta_j - \theta_{ij}) \quad (7)$$

$$Q_{gi} = Q_i + V_i \sum_{j=1}^{NB} V_j Y_{ij} \sin(\delta_i - \delta_j - \theta_{ij}) \quad (8)$$

1) *Voltage Limit*: The limit of voltage magnitudes in MG buses can mathematically be expressed by [6],

$$V_{\min} \leq V_i \leq V_{\max} \quad (9)$$

2) *Thermal Limit*: The thermal limit can be obtained by limiting current flow in network lines as expressed by,

$$I_i \leq I_i^{\max} \quad i = 1, \ldots, N_{Br}. \quad (10)$$

3) *Power Generation Limit of DGs:* For an islanded MG with a droop controller the power generation limit can be obtained by limiting active, reactive and nominal power as follows, respectively.

$$P_{gi} \leq P_{gi}^{\max} \quad (11)$$

$$Q_{gi} \leq Q_{gi}^{\max} \quad (12)$$

$$P_{gi}^2 + Q_{gi}^2 \leq S_{gi}^{\max} \quad (13)$$

where P_{gi} and Q_{gi} can be obtained by (A3) and (A4). In the case where the active and reactive generated power reach to their maximum values P_{gi} and Q_{gi} are set to $P_{gi}^{\max}$ and $Q_{gi}^{\max}$ and the droop controller converts to a PQ bus controller.

4. Proposed solution

In this paper, finding location and operation of DG units in autonomous MG were formulated as a multi-objective optimization problem. To solve this multi-objective problem a novel method is proposed. The method is underpinned as follows:

i) Proposing an optimization algorithm based on a combination of HS and GA.
ii) Developing a load flow algorithm for autonomous MG based on droop, PQ and PV control.
iii) Applying a fuzzy method to find the best HM and the best final solution. Noting that, the HM is a memory place that includes the set of decision parameters (vector of control parameters of each DG and their installation locations).

A. Proposed optimization method

To propose the paper optimization method, the harmonic search, HS, algorithm is adopted. Although HS is regarded as one popular optimization approach it has some deficiency due to its low speed divergence and sticking in local optimal solutions. To cope with such deficiency HS is combined with genetic algorithm, GA, to provide a new optimization algorithm. The combination of HS and GA is based on adding two GA operators, namely, mutation and crossover, to HS [26,27]. Mutation is typically exploitative; that is, it generates random small diversions. Thus, the new solution stays near the parent and promising region. Crossover is typically explorative; that is it generates random big diversions. Thus, the new solution jumps to a region between two parents. Compared with HS, the proposed method, HS-GA, enables to effectively provide searching of solution region and to reduce convergence calculation time in local minima region.

The underlying principles of HS-GA can be discussed in terms of three harmony memories, namely HM_1, HM_2 and HM_3. Firstly HM_1 is generated similar to what is done in conventional HS method. Then harmony vectors in HM_1 are used as the prior step as parents of GA so that crossover and mutation operators of GA are applied to HM_1 to provide new harmony vectors which saved in harmony memory called HM_2. Finally, harmony vectors in HM_1 and HM_2 are compared according to the objective function fitness together to find the best solution which is saved in harmony memory called HM_3. It may be remarked that in the HS approach HM_1 is considered as a next generation, in the HS-GA approach, HM_3 is considered as a next generation.

The steps of HS-GA can be outlined as follows that shown in Fig. 3.

Step 1: Input microgrid parameters.
Step 2 (Initialization of HS): Set the t = 0 and produce answer vectors in the HM_1 that show candidate buses for DG locations and control parameters.

$$x_i^j = x_i^{\min} + rand(0,1)*\left(x_i^{\max} - x_i^{\min}\right) \quad j = 1, \ldots, \text{HMS}. \quad (14)$$

Step 3 (Power flow): calculate power flow for each answer vectors to calculate voltage stability, generated power cost and voltage deviation.
Step 4 (fuzzy): Compute the fitness of each objective function using fuzzy technique (16) and determineμ_{f_1}, μ_{f_2} and μ_{f_3} based on f_1, f_2 and f_3.
Step 5 (fitness evaluation): Use (19) to calculate the objective function.
Step 6 (time updating): update the time counter t = t + 1.
Step 7: Create new vector (x_{new}) in HM_1 based on:
- Generate a random number (M) in the range [0, 1].
- If M < HMCR, generate variable x_{newi} of the memory consideration (HM_1).
- With a probability PAR modify x_{newi} by a small amount according to [30]:

$$x_{newi} = x_{newi} + M*BW \quad (15)$$

- If M > HMCR, generate variable x_{newi} by a random choice of admissible region.
- If the fitness function of the new harmony vector x_{new} is better than the worst harmony vector in HM_1, change vector position in HM_1.
- Save fitness of each vector in HM_1

Step 8 (Initialization of GA): Generate harmonies for GA using HM_1vectors that they are such as parents in GA.
Step 9: Make new harmonies by crossover and mutation operators using GA method and they save in HM_2.
Step 10 (Elitism): Produce new vector in HM_3 based on:

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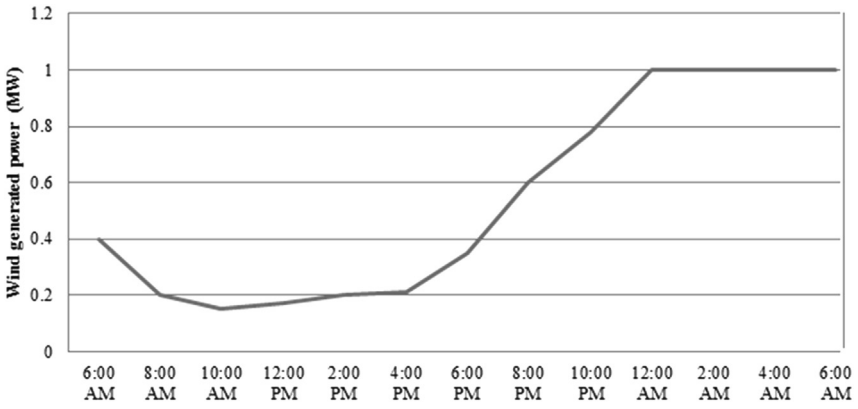


Fig. 2. Wind speed profile.

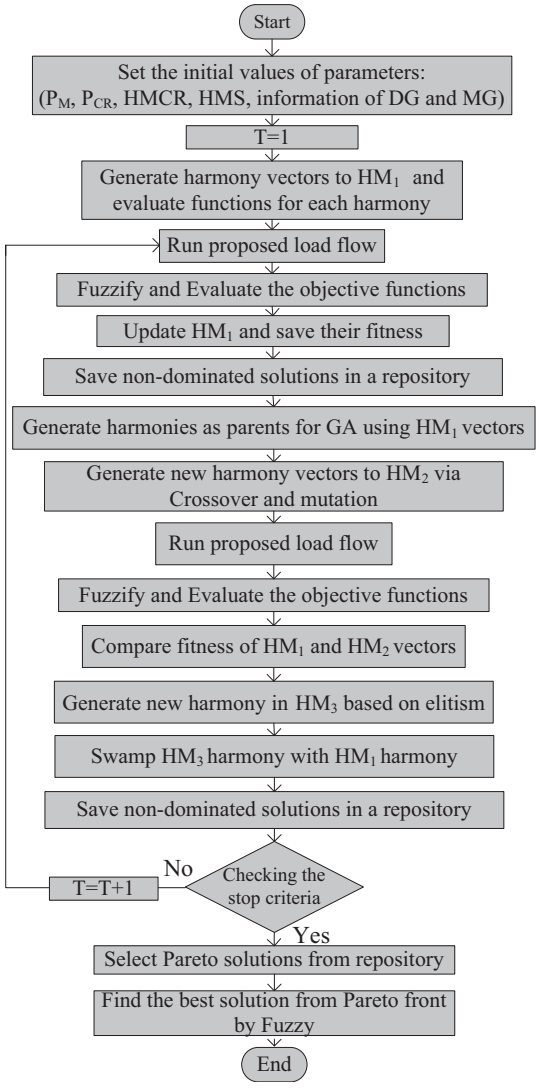


Fig. 3. The HS-GA algorithm for planning MG operation.

- Merging together the HM_1 vectors and the generated population in HM_2 of GA.
- Calculate a power flow for answer vectors of the HM_2.

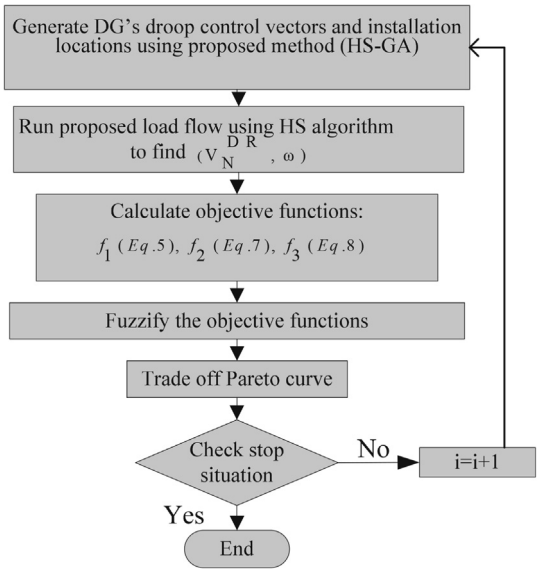


Fig. 4. Procedures of proposed solution for autonomous MG optimization.

- Determine the fitness of each objective function using fuzzy method (16).
- Sorting them in descending order of fitness value and permit the best vectors to be chosen for HM_3 based on the fitness of HM_1 and HM_2 vectors to continue the optimization process.

Step 11: Update repository and HM_1based on:

- The swap of the position of vectors in HM_1 with HM_3
- The identification all the non-dominated and saving in the repository based on (17) and (18).

Step 12 (End): If the ending criterion is not met go to step 6.

It might be noted that Steps 9 to 11 are what added to the conventional HS in the paper approach. To calculate the objective functions in HS-GA iteration the new proposed load flow as discussed below should be run.

B. Proposed load flow in autonomous MGs

In practice, Newton-Raphson and Fast-Decoupled are of frequent use to calculate the power flow in the system. To cope with such divergence problem a number of algorithms have been proposed [4–8]. Unfortunately, the use of such algorithm faces two issues, namely the slack bus consideration issue and lack of droop

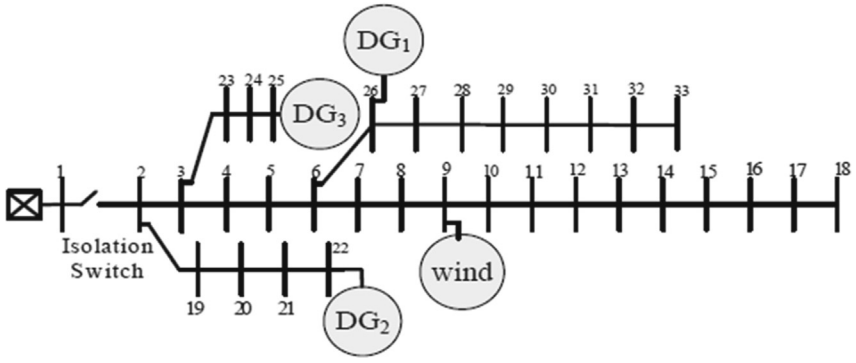


Fig. 5. A 33-bus-islanded microgrid system.

Table 1
Data of DG units based on droop controller a 33-bus system.

DGs	S_{max} (MVA)	q_{MAX} (Mvar)	Cost ($/kwh)
1	2	1.20	7.705
2	1	0.60	11.731
3	1.5	0.90	10.363
Wind Generator (WG)	1	0.55	–

Table 2
HS-GA parameters.

HMS	Iteration	CR	BW	PAR	HMCR	F
15	25	0.4	0.02	0.3	0.7	0.40

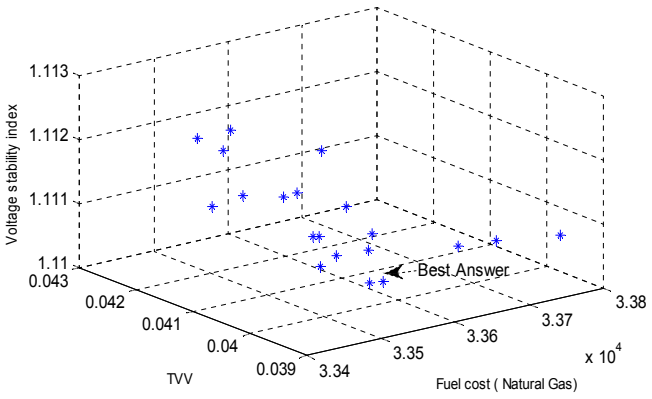


Fig. 6. Pareto front solution of HS-GA algorithm (p.u.).

bus consideration issue. Therefore, it is required to reformulate the power flow problem so that the droop bus is considered rather than slack bus. The Appendix proposes a new formula for the power flow analysis problem in an islanded microgrid to model different control modes of DGs, such as droop and PQ. The development is based on assuming steady state frequency as an unknown variable (this frequency is calculated by the proposed method and then it becomes known and constant) and introducing droop buses in addition to PV and PQ buses.

C. Three fuzzy-subordination functions

One is in finding the best solution of the optimal objective functions from their set of Pareto front solutions and the second is in finding the best HM from its two vectors provided by GA and HS. For the set of Pareto front solutions, fuzzy membership functions can be given by,

$$\mu_{f_i} = \begin{cases} 1 & f_i \le f_i^{\min} \\ \dfrac{f_i^{\max} - f_i}{f_i^{\max} - f_i^{\min}} & f_i^{\min} \le f_i \le f_i^{\max} \\ 0 & f_i \ge f_i^{\max} \end{cases} \quad \mathrm{i} = 1,\ 2,\ 3 \tag{16}$$

where μ_{f_i} is the fuzzy subordination of f_i and $f_i^{\min}$ and $f_i^{\max}$ are the best and worst solutions of f_i, respectively. A linear − partition of a fall half trapezoid is used for fuzzy membership functions. To solve multi-objective functions, in each iteration, there is a set of non-dominated answers should be kept in a repository. The answer x_1 dominates x_2 if equations (17) and (18) are warranted.

$$f_n(x_1) \le f_n(x_2) \quad \forall n \in \{1, 2, \ldots, \tau\} \tag{17}$$

$$f_m(x_1) < f_m(x_2) \quad \exists m \in \{1, 2, \ldots, \tau\} \tag{18}$$

where x represents solutions, droop parameters and sitting of DGs. To evaluate each individual in the repository the following normalized function can be used

$$\lambda_\mu(n) = \frac{\sum_{i=1}^{N_{obj}} \kappa_i * \mu_{f_i}(x_n)}{\sum_{n=1}^{N_{rep}} \sum_{i=1}^{N_{obj}} \kappa_i * \mu_{f_i}(x_n)} \tag{19}$$

The (19) is used to sort the non-dominated solutions according to the decision maker preference for all objective functions.

D. Wind generator modeling

For wind power quantification three basic characteristics are essential: wind direction and speed, the topographic characteristics of the study environment and the air density [36]. Between these aspects, the wind speed is the mainly significant one. The Fig. 2 shows a wind speed profile provided in this paper. The output generated power of a wind unit, shown by P_{wind}, based on variations of speed can be calculated by

$$P_{wind,t} = \begin{cases} 0 & 0 \le V_t < v_I \\ \beta \dfrac{V_t - v_I}{v_r - v_I} & v_I \le V_t < v_r \\ \beta & v_r \le V_t < v_o \\ 0 & v_o \le V_t \end{cases} \tag{20}$$

The procedures of the proposed method can be summarized in

Table 3
Values of droop control parameters of the DGs in 33-bus mg.

DGs	HS-GA				HS			
	Sp	Sq	V*	ω^*	Sp	Sq	V*	ω^*
1	5.9894E-4	9.591E-4	1.0040	0.99967	7.4410E-4	1.2116E-3	1.0035	0.99974
2	3.3519E-4	0.01228	1.00831	0.99877	3.0488E-4	0.01795	1.0045	0.99861
3	1.4342E-3	1.5384E-4	1.0082	1.0001	1.3613E-3	1.3326E-4	1.0117	1.00010
4	2.2694E-3	5.8228E-3	1.0014	1.0002	2.4138E-3	5.3435E-3	0.9991	0.99998
	GA				PD			
	Sp	Sq	V*	ω^*	Sp	Sq	V*	ω^*
1	9.43396E-4	9.4869E-3	1.0120	1.0002	1.1151E-3	0.025	1.015	1.000
2	6.4189E-4	2.8986E-3	1.0027	0.99889	2.2284E-3	0.050		
3	1.1064E-3	1.9608E-3	1.0134	1.0000	1.4863E-3	0.0333		
4	2.5877E-3	5.03778E-3	1.0007	1.0005	2.9712E-3	0.0667		

Table 4
Values of steady state frequency.

Methods	HS-GA	HS	GA	PD
Steady state frequency	0.99865	0.99851	0.99870	0.99840

Ref. [25] with total active and reactive loads of 3.715 MW and 2.30 MVar, respectively. Four DGs were set on buses 26, 22, 25 and 9. The Data of DG units and fuel (gas) prices is shown in Table 1. Also, the parameters of the proposed method are given in Table 2.

Table 5
Generated Power (P_{DG} (MW), Q_{DG} (Mvar)) of DGs for different methods.

Method	P_{DG1}	Q_{DG1}	P_{DG2}	Q_{DG2}	P_{DG3}	Q_{DG3}	P_{WG}	Q_{WG}
HS-GA	1.7087	1.0431	0.3587	0.2426	1.0085	0.6533	0.6789	0.3927
HS	1.6492	1.0688	0.3292	0.1179	1.1691	0.7485	0.6093	0.3976
GA	1.5916	1.0297	0.2913	0.11387	1.1819	0.7699	0.6917	0.3889
PD	1.4375	0.5814	0.7172	0.4906	1.0752	0.8212	0.5379	0.4504

Table 6
Comparison among objective functions of proposed algorithm and other methods.

Objective function	HS-GA	HS	GA	PD	Newton-trust [37]
f_1 ($/h)	33586.73	33857.87	33795.06	35250.32	33829.03
f_2 (p.u.)	1.1103	1.1139	1.1141	1.1533	1.1125
f_3 (p.u.)	0.0401	0.0455	0.0422	0.0724	0.0526

Table 7
Generated and losses active and reactive power, (P (MW), Q (Mvar)).

Method	P_{DG}	Q_{DG}	P_{Loss}	Q_{loss}
HS-GA	3.754	2.3320	0.0398	0.0317
HS	3.758	2.3334	0.0421	0.0329
GA	3.7566	2.3330	0.0417	0.0328
PD	3.7678	2.3434	0.0528	0.0436

Fig. 4.

5. Numerical results and discussion

Two case studies, based on autonomous operation were examined and simulated in MATLAB to evaluate the performance of the proposed method. In the first case, a 33-bus system, solely the optimal DG's droop parameters based on droop control were identified and it was assumed that the locations of DGs are pre-specified. In the second case, a 69-bus system, both optimal droop parameters and locations of DGs were identified. The DG units are gas turbines based on synchronous generators.

A. 33-bus microgrid

The first system, a 33-bus system, shown in Fig. 5, was used from

The performance of the proposed method was compared with those of HS and GA. Also, the performance of the proposed method was compared with a method that the parameters of DGs were pre-determined (PD) without conducting any optimization process. This method is called the pre-determined method. In all methods, the proposed power flow was used and comparison was done

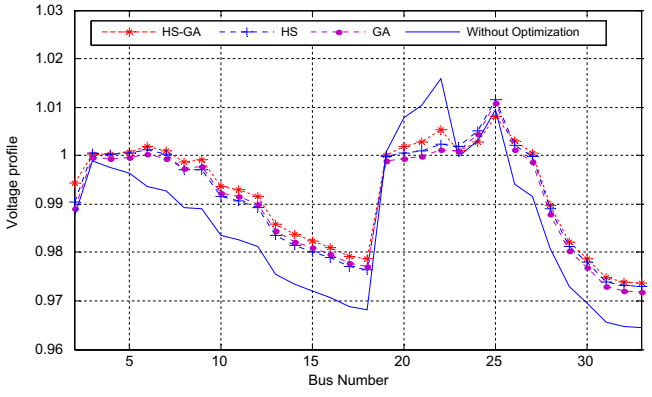


Fig. 7. Voltage profile of MG buses for different methods.

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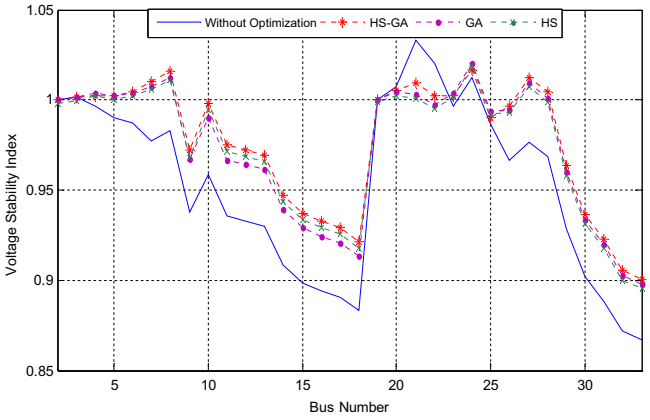


Fig. 8. Voltage stability index of MG buses for different methods.

utility function is shown.

Table 3 shows the results for the values of droop control parameters of the DGs obtained by HS, GA and HS-GA. The allowable frequency and voltage deviation for the pre-determined method were considered to be 0.5%–5% of the nominal values, respectively. For this method, the values of ω^* and V^* were considered so that the power demands and security conditions of MG in the load flow algorithm were met. Table 4 gives the values of steady state frequency calculated by each method. This table demonstrates that all the frequency values satisfied the constraints. Table 5 compares the results for DGs generated power calculated by each method.

Table 6 compares the values of objective functions calculated by the proposed method and other methods. This table shows that the proposed method provided the lowest (best) values of objective functions and the pre-determined method provided the highest (worst) values. This supports the effectiveness of the proposed

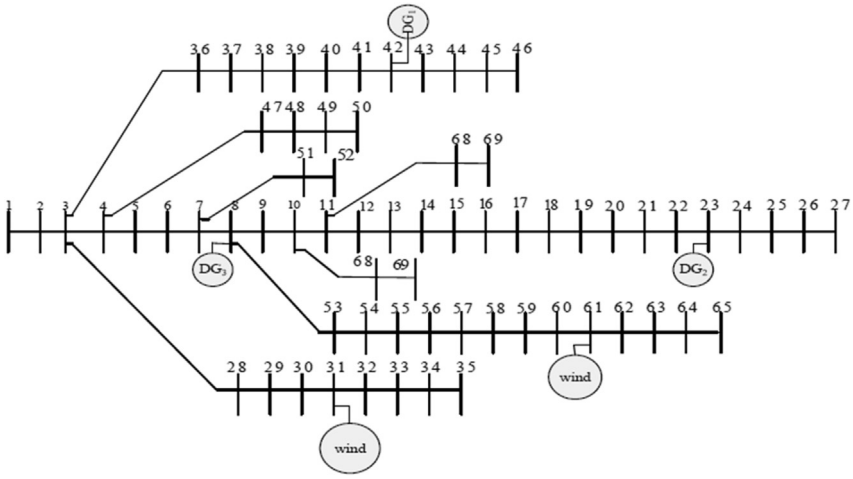


Fig. 9. The 69-bus islanded microgrid test system.

Table 8
Data of DG units based on droop controller for a 69- bus system.

DGs	S_{max} (MVA)	q_{MAX} (Mvar)	Cost ($/kwh)
1	1.5	0.90	7.705
2	0.5	0.30	8.731
3	1.0	0.60	8.363
Wind generator (WG_1)	1	0.45	–
Wind generator (WG_2)	1	0.45	–

based on the best solution. In doing so, first the Pareto front solution of each method was obtained and then using a Fuzzy approach the best solution was determined. Fig. 6 shows an efficient frontier as a 3-dimensional plane and the best answer based on the fuzzy method. It is marked that if solely cost was considered as the optimization objective, then DG1 should be identified as the most generated power followed by DG_4, DG_3 and DG_2 due to their fuel price, shown in Table 1. However, as other objectives, voltage profile and stability index, were also of interest, as shown in Table 6, the generated power from high to low were identified as DG_1, DG_3, DG_4 and DG_2, as shown in Table 5. This demonstrates the necessity of considering multi-objective functions in finding optimum location and operation of DGs. Table 7 illustrates the total power generated by DGs and power losses of the system calculated by each method. This table shows that the proposed method has the lowest active and reactive power losses compared with other methods implying that the proposed method is more effective in setting droop parameters of DG units in the steady state operation.

Table 9
Comparison among optimization algorithms in tunning droop controller parameters of DGs.

DGs	HS-GA				HS				GA			
	Sp	Sq	V^*	ω^*	Sp	Sq	V^*	ω^*	Sp	Sq	V^*	ω^*
1	1.4846E-3	2.2681E-3	1.0102	0.99907	1.1684E-3	3.2299E-3	1.0207	1.0003	1.4431E-3	1.7563E-3	1.0280	1.0001
2	3.3654E-3	5.9089E-3	1.0087	0.99880	6.1092E-4	3.1266E-3	1.0250	0.99901	9.4195E-4	5.6980E-3	1.0040	0.99904
3	2.2418E-3	6.2919E-3	1.0100	0.9990	1.5504E-3	1.5251E-3	1.0091	1.0004	2.1628E-3	4.9297E-3	0.9950	1.0001
4	8.8386E-4	0.03618	1.0270	0.99811	2.17544E-3	5.6259E-3	1.0280	1.0004	2.2869E-3	0.02991	1.0220	1.0004
5	8.7212E-5	2.6283E-3	0.9984	0.99755	1.3197E-3	1.8614E-3	1.0090	1.0001	4.5947E-4	1.5085E-3	1.0005	0.9990

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Table 10
Comparison among objective functions of proposed algorithm and other methods.

Index	Methods		
	HS-GA	HS	GA
f_1 ($)	244274319	245936573	244966195
f_2 (p.u.)	1.0197	1.0186	1.1141
f_3 (p.u.)	0.0203	0.0744	0.0422

Table 11
Values of steady state frequency.

Methods	HS-GA	HS	GA
Steady state frequency	0.99747	0.99885	0.99861

B. 69-bus microgrid

The second system, a 69-bus system, shown in Fig. 9, was used from Ref. [28] with total active and reactive loads of 3.772 MW and 2.694 MVar, respectively and with optimal locations of five DGs. The data of DG units and fuel (gas) prices is based on [24]. These parameters include reference voltage and frequency as well as static droop gains of DGs. The data of DG units and fuel (gas) prices is shown in Table 8.

Table 9 shows the optimized values in tuning droop controller parameters of DGs based on different optimization methods. It should be noted that these values are the optimization variables as introduced in section 3. The generated power based on calculated variables in Table 9 is provided (See Table 12).

Table 12
The generated active and reactive powers of each DG for a 69-bus (P (MW), Q (MVAR)).

Method	P_{DG1}	Q_{DG1}	P_{DG2}	Q_{DG2}	P_{DG3}	Q_{DG3}	P_{WG1}	Q_{WG1}	P_{WG2}	Q_{WG2}
HS-GA	1.1013	0.7877	0.3235	0.2895	0.7020	0.4784	0.7446	0.5100	0.9404	0.6489
HS	1.2406	0.8744	0.2605	0.1962	0.6513	0.4656	0.7104	0.4948	0.9512	0.6960
GA	1.0304	0.7430	0.4614	0.2140	0.6903	0.5529	0.7815	0.5538	0.8509	0.6633

Table 13
The total generated active and reactive powers and losses for a 69-bus (P (MW), Q (MVAR)).

Methods	P_{DG}	Q_{DG}	P_{Loss}	Q_{loss}
HS-GA	3.8117	2.7256	0.0398	0.0317
HS	3.8140	2.7268	0.0421	0.0329
GA	3.8137	2.7267	0.0417	0.0328

Figs. 7 and 8 show the voltage profile and VSI of MG provided by HS-GA and other methods, respectively. Fig. 7 demonstrates that HS-GA give the best voltage profile while the pre-determined method provides the worst. This figure also demonstrates that using optimization methods enhances the voltage profile at majority buses; this is of particular importance in bus 18. Similarly, Fig. 8 demonstrates that HS-GA gives the best VSI while the pre-determined method provides the worst. This figure also shows that using optimal parameters for DGs help in improving VSI.

The other significance of the paper approach can be discussed in terms of setting droop parameters of DGs as they are regarded as the main driver to control the voltage and frequency of islanded MG and to share power among DGs. In doing so, droop parameters are captured as unknown variables and their optimal values are calculated by HS-GA to minimize the objective functions. For example, see Table 3 for the results of optimal tuning of droop parameters. Also see Figs. 7 and 8 for comparing the results of objective functions with and without optimizing such parameters. The obtained results in 33-bus system are compared with Newton trust method based on [37]. The results are shown in Table 6. The HS-GA has the better improvement in operation of MG.

Table 11 gives the values of steady state frequency calculated by each method where all the frequency values satisfied the constraints. Table 12 compares the results for DGs generated power calculated by each method. Table 10compares the values of objective functions calculated by the proposed method and other methods. This table shows that the proposed method performs better than the other methods. For example, Table 10 shows the fuel cost (f_1), in a yearly basis, obtained by HS-GA is the lowest while that of HS is the highest. In addition, Table 13 illustrates the total power generated by DGs and power losses of the system calculated by each method. This table shows that the proposed method has the lowest active power loss.

To conduct some statistical analysis the standard deviations (SD), the best mean (BM) and the worst value (WV) of the objective functions of the 69-bus system with 60 runs for GA-HS, HS and GA are calculated as shown in Table 14. The best mean demonstrates the convergence ability while the standard deviation shows the stability of methods [36].

It should be mentioned that a fuzzy approach is employed in this paper to find the best solution from a set of Pareto front answers. For instance, see Table 14 for having a comparison between different optimization methods provided based on three indexes, SD, BM and WV, where the proposed gives a better performance. Table 14 shows the lowest SD index for HS-GA implying uniformity of results provided by HS-GA. This table also shows the lowest BM and WV indices for HS-GA implying HS-GA ability in handling effectively interdependence relationships among decision variables.

Furthermore, Tables 6 and 10 demonstrate that HS-GA is capable of providing the lowest values for the objective functions compared with HS and GA.

Table 14
Statistical analysis results for different methods.

	HS-GA			HS			GA		
	SD (%)	BM	WV	SD (%)	BM	WV	SD (%)	BM	WV
f_1 ($)	1.41	2447E5	2449E5	2.03	2463E5	2482E5	2.59	2451E5	2474E5
f_2 (p.u.)	1.01	1.117	1.204	1.64	1.091	1.286	1.54	1.215	1.375
f_3 (p.u.)	0.55	0.0379	0.0394	0.87	0.0861	0.091	0.94	0.0683	0.0731

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6. Conclusion

In this paper, a new method for finding the location and operation of DGs of autonomous microgrids based on droop control was proposed. The idea was to deal with the issues of conventional methods which are unable to cope with isolated MGs. The significance of the paper approach is against conventional methods. Also, the paper approach can be discussed in terms of setting droop parameters of DGs as they are regarded as the main driver to control the voltage and frequency of islanded MG and to share power among DGs. In doing so, droop parameters are captured as unknown variables and their optimal values are calculated by HS-GA to minimize the objective functions. In addition, two issues exist in the conventional power flow, the slack bus and the lack of droop bus consideration issues are addressed in the paper to calculate the optimal values of droop controller parameters. The other significance of the paper is that it gives an extension of HS algorithm by adopting mutation and crossover operators of GA in HS. This enhances HS in exploring and exploiting of solution in different cases more effectively.

Appendix

Proposed Power Flow Algorithm

Calculation for PQ Buses: In this paper, the model of [28] is adopted and modified to deal with PQ buses. The value of the bus voltage magnitude and phase angle can be obtained, respectively, by,

$$V_j^2 = \sqrt{\left(\left[rP_j + x(\omega)\cdot Q_j - \frac{V_i^2}{2}\right]^2 - \left[r^2 + x^2\right]\cdot\left[P_j^2 + Q_j^2\right]\right)} - \left[rP_j + x(\omega)\cdot Q_j - \frac{V_i^2}{2}\right] \tag{A1}$$

$$\delta_j = \delta_i - \sin^{-1}\left(\frac{x(\omega)P_j - rQ_j}{V_i V_j}\right) \tag{A2}$$

Calculation for droop Buses: Unknown variables of a droop bus, as shown in Fig. 10, might be outlined as active and reactive power, voltage magnitude and angle. The values of power injection of bus j, shown in Fig. 10, can be given by,

$$P_j = -P_{DG} + P_{load} + P_T \tag{A3}$$

$$Q_j = -Q_{DG} + Q_{load} + Q_T \tag{A4}$$

Active and reactive power sharing depends on the frequency and local voltage of each DG unit, and can be given by,

$$P_{DGi} = \frac{1}{s_{p_i}}\left(\omega_i^* - \omega\right) \tag{A5}$$

$$Q_{DGi} = \frac{1}{s_{q_i}}\left(\left|V_i^*\right| - V_i\right) \tag{A6}$$

To calculate the receiving end bus phase angle (A2) is used where P_j and Q_j are given by (A3) and (A4). This is valid for the case where P_j and Q_j are within the permitted limit of DG units. Otherwise, P_j and Q_j need to be treated as known variables in which their values are equal to their corresponding limit values. There follows the receiving end bus is converted from the droop control mode to the PQ mode. Therefore, the power flow problem needs to be resolved for the bus phase angle and voltage magnitude.

Proposed Load Flow Solution in Autonomous MG: The goal of the optimization problem is to minimize the sum of absolute mismatch values of active and reactive power,

$$f(x,u) = k_1\left|\sum_{i=1}^{n_{bus}}\Delta P_i\right| + k_2\left|\sum_{i=1}^{n_{bus}}\Delta Q_i\right| \tag{A7}$$

where x and u are the vectors of state and control variables, and they can be calculated, respectively, by,

$$\boldsymbol{x} = \left[\delta \quad V_L^{PQ} \quad P_{DG}^{DR} \quad Q_{DG}^{DR}\right] \tag{A8}$$

$$\boldsymbol{u} = \left[\omega \quad V_1^{DR} \quad \ldots \quad V_N^{DR}\right] \tag{A9}$$

Here δ and V_L^{PQ} are the voltage angle and magnitude of the PQ bus; P_{DG}^{DR} and Q_{DG}^{DR} are the generated active and reactive power of the droop bus; V^{DR} is the voltage of the droop bus; ω is the system frequency; and N is the number of buses with a droop controller. n_{bus} is number of buses. k_1 and k_2 are penalty coefficients for the objective function. In (A7), ΔP_i and ΔQ_i are power mismatches and they can be calculated, respectively, by,

$$\Delta P_i = P_{DG_i} - P_{load_i} - \sum_j V_i V_j Y_{ij}(\omega)\cos\left(\delta_i - \delta_j - \theta_{ij}\right) \tag{A10}$$

$$\Delta Q_i = Q_{DG_i} - Q_{load_i} - \sum_j V_i V_j Y_{ij}(\omega)\sin\left(\delta_i - \delta_j - \theta_{ij}\right) \tag{A11}$$

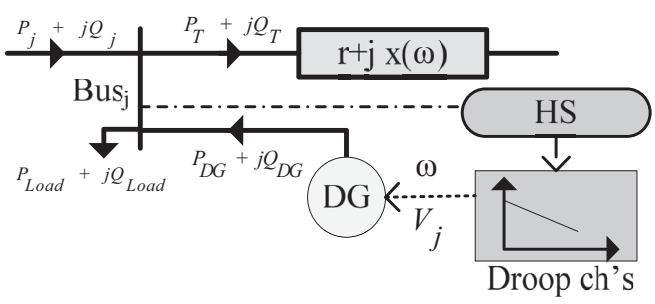


Fig. 10. Injected power of DG to bus j based on droop.

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Nomenclature

BW: Distance bandwidth
HMCR: Harmony memory considering rate
HMS: Harmony memory size
PAR: Pitch adjusting rate
$C_m(P_{DGi})$: Fuel consumption of DG_i
I_i, I_i^{max}: Current and rated current of line *i*
κ_i: The decision maker preference for all objective functions
N_{obj}: Number of objective functions
N_{rep}: Number of solutions in repository
NB: Number of buses
N_{dr}: Number of DGs with droop control
P_i, Q_i: Demand active and reactive powers of bus *i*
P_{gi}, Q_{gi}: Active and reactive power delivered to bus i
P_{i+1},Q_{i+1}: Total active and reactive power at bus $i+1$
P_{gi}^{max}: Maximum active power of DG_i
P_j: Injected active power to bus *j*
Q_{gi}^{max}: Maximum reactive power of DG_i
Q_j: Injected reactive power to bus *j*
R_i, X_i: Resistance and reactance of line *i*
S_{gi}^{max}: Maximum apparent power of DG_i
S_p, S_q: Active and reactive power static droop gain
t: Time index
V_{min}, V_{max}: Maximum and minim bus voltage
$\left|V_i^*\right|$: Voltage magnitude of DG_i at no load
$Y_{ij}(\omega)$: The ijth element of admittance matrix
δ_i: Phase angle of voltage at bus *i*
ω_i^*: Angular frequency of DG_i at no load
θij: Phase angle
μ_{fi}: The degree of desirability
λ_μ: The normalized function

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