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Research Article

Optimal clustering of MGs based on droop controller for improving reliability using a hybrid of harmony search and genetic algorithms

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ABSTRACT

This paper proposes a novel method to address reliability and technical problems of microgrids (MGs) based on designing a number of self-adequate autonomous sub-MGs via adopting MGs clustering thinking. In doing so, a multi-objective optimization problem is developed where power losses reduction, voltage profile improvement and reliability enhancement are considered as the objective functions. To solve the optimization problem a hybrid algorithm, named HS-GA, is provided, based on genetic and harmony search algorithms, and a load flow method is given to model different types of DGs as droop controller. The performance of the proposed method is evaluated in two case studies. The results provide support for the performance of the proposed method.

1. Introduction

The emergence of economic and environmental problems connected to the electrical energy consumption growth and the existence of some deficiently associated with the use of conventional methods in producing electrical energy [1] has encouraged the development of new power networks, such as MGs, for supplying power to local loads [2,3]. However, concerns remain about an effective design of MGs to deal with the technical, economical and reliability problems of MGs [4,5].

A number of researchers have put forward optimization models for formulation MGs design problems based on technical and economic requirements. For example, the research of [6] and [7] gives a model for minimizing power losses of MGs, that of [8,9] discusses the improvement of MGs' voltage profile, and the studies of [10–12] look at minimizing MGs' investment costs. In such optimization models, different techniques are adopted such as index-based techniques [13], mixed integer non-linear programming [14], analytical techniques [15], genetic algorithm (GA) [16,17], harmony search [18], particle swarm optimization (PSO) [19], evolutionary programming [20], Pareto frontier differential evolution algorithm (PDE) [21], and artificial bee colony (ABC) [22].

To address the reliability problem of autonomous MGs, one way is to design the MG with an ability to be divided into a number of sub-MGs when a fault happens in the MG; this might be called clustering of a given MG [3,22] which makes it more reliable. Clustering allows sub-MGs to operate self-adequate with a low imbalance value between the active and reactive power of demand and generation. A self-adequate sub-MG is able to protect itself when a fault happens in other sub-MGs, via disconnecting from such sub-MGs resulting in a higher reliability and power quality for its consumers. Equivalently, preventing any disturbance propagation to other sub-MGs is the main benefit of the design of self-adequate sub-MGs. Adopting clustering approaches in practice, however, comes with some difficulties. One major challenge in a clustering approach is how to design a given MG so that energy transferring among sub-MGs or generation-load unbalancing in each sub-MG yields to a minimum value while at the same time technical or other requirements of the MG are satisfied.

Interestingly, a review of the literature reveals few studies thinking in terms of the clustering approach, to address technical and reliability problems of an autonomous MG despite such problems being widespread [3,22]. The study of [3] makes a MG cluster by finding the optimal location of DGs along with cut set lines to minimize transmitted power between them. In [3], the technical requirement is considered as the objective function and the Tabu search method is used to solve the optimization problem.

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Nomenclature

i, j	Bus indices
m	Unknown variables index
N_{dr}	Number of DGs base on droop controller
x_{DG}	Location vector of DGs
x_k	Vector of DGs' droop controller parameters
x_{br}	Branch vector of virtual cut set lines
$\lvert V_i^* \rvert$	Nominal value of voltage magnitude
ω^*,ω	Nominal and operational values of frequency
S_p , S_q	Active and reactive power static droop gains
dr	DGs' droop operation index
PQ	DGs' constant power operation
Cap	Capacitance index
P_{gi}, Q_{gi}	Generated active and reactive power at bus i (MW and MVAR)
P_i, Q_i	Demand active and reactive power at bus i (MW and MVAR)
P_{DG}	Active power rating of DGs (MW)
Y_{ij}	Magnitude of the ijth element of admittance matrix
V_i	Voltage magnitude of the ith bus (KV)
V_{min},V_{max}	Minimum and maximum bus voltage (KV)
R_i	Resistance of branch i (Ω)
X_i	Reactance of branch i (Ω)
NB	Number of buses
N_{DG}	Number of DGs
P_{index}	Active power of virtual cut set lines (MW)
Q_{index}	Reactive power of virtual cut set lines (MVAR)
α, β	Weighting factors
N_{MGs}	Number of sub-MGs
N_{Br}	Number of lines
δ_i	Phase angle of voltage at bus i
δ_{min}, δ_{max}	Minimum and maximum phase angle (degree)
$\hat{P}_{i+1}$,$\hat{Q}_{i+1}$	Active and reactive power of load at bus $i+1$ (MW, MVAR)
θ_{ij}	Phase angle of the ijth element of matrix Y (degree)
I_i,I_i^{max}	Current and rated current of branch i (in amperes)
LFI	Load flow index
HMS	Harmony memory size
PAR	Pitch adjusting rate
HMCR	Harmony memory rate
BW	Distance bandwidth
t	Time index
PQ	Constant power
V_L^{PQ}, $\cdot V^{DR}$	Magnitude of PQ and droop buses
P_{DG}^{DR}, $\cdot Q_{DG}^{DR}$	Generated active and reactive power of droop buses
k_1 , k_2	Penalty coefficients
S	Variable of unknown parameters

In comparison, the research of [22] looks at MG clustering based on finding the optimal location of DGs where operating costs of MGs are considered as the objective function, and the ABC algorithm is used to solve the optimization problem. Despite the seminal works of [3] and [22], however, they fail to consider technical and reliability problems of MGs simultaneously, they also treat power as a constant value and they thus ignore to consider droop control parameters of DGs as variables.

Despite MGs clustering can be seen as one effective tool for improving MGs reliability, there is little effort on what the optimal clustering is and how clustering improves MGs reliability. No literature appears to have focused on both reliability and technical problems of MGs simultaneously via adopting MGs clustering thinking. In such light, this paper formulates a novel multi-objective optimization problem for addressing technical and reliability problems associated with the design of an autonomous MG based on MG's clustering thinking. Power losses reduction and voltage profile improvement are considered as MG's technical problems while increasing the MG's clustering ability is regarded as the MG's reliability problem. These are treated as the objectives of the optimization problem where the variables include DGs and capacitances locations, droop parameters of DGs operating based on droop controller, and cut set lines locations. In this paper cut set lines refer to those lines in a MG which need to be disconnected when a fault happens in it and then the MG is clustered to a number of sub-MGs. To solve the optimization problem a hybrid algorithm, named HS-GA, is proposed based on genetic and harmony search algorithms to give non-dominated solutions as Pareto front with fast convergence and without falling in local optimal values. To find the best solution from Pareto front a fuzzy function is provided. In order to run HS-GA, a new load flow algorithm is developed to model different types of DGs as PQ buses with constant power and droop controller buses.

The contributions of the paper, in summary, are:

1. The paper proposes an original solution to the problem of optimal design of an autonomous MG using clustering thinking, thereby contributing to knowledge on MGs' design in power.
2. The paper gives an optimal way for determining cut set lines to convert a MG to a number of sub-MGs to secure the MG against any fault, contributing to the robustness of MGs.
3. The paper presents the idea of using DGs based on droop in MGs and optimal droop parameters of DGs, attributing to optimal control of frequency and voltage of MGs.
4. The paper provides a new hybrid algorithm, HS-GA, based on genetic and harmony search algorithms to solve the optimization problem.
5. The paper opens up to the power industry a new way of thinking about MGs reliability based on clustering thinking.

This paper is divided into 6 thematic sections. The problem formulation is given in Section 2. Section 3 provides a solution of the optimization problem and a load flow method for the autonomous operation of sub-MGs is explained in Section 4. The numerical results are presented in Section 5 and finally the conclusion is given in Section 6.

2. Problem formulation

In order to address technical and reliability problems of MGs based on clustering thinking a multi-objective problem involving three objective functions are formulated. Two objectives are related to technical aspects of MGs, including power losses (f_1) reduction and voltage stability index (f_2) improvement. The third objective is associated with the MG's reliability (f_3) improvement via finding optimal cut set lines in the MG in order to cluster it to a set of sub-MGs which is conducted by minimizing active and reactive power unbalancing in each sub-MG. The variables of this optimization problem involve the location and sizing of DGs and capacitances, droop controller parameters of DGs, and virtual cut-set lines of sub-MGs.

The optimization problem can be mathematically expressed by,

$$\min_{\{S\}} \{f_1(S), f_2(S), f_3(S)\} \tag{1}$$

$$P_{gi}(S) = P_i(S) + V_i(S) \sum_{j=1}^{NB} V_j(S) Y_{ij} \cos(\delta_i - \delta_j - \theta_{ij}) \quad (2)$$

$$Q_{gi}(S) = Q_i(S) + V_i(S) \sum_{j=1}^{NB} V_j(S) Y_{ij} \sin(\delta_i - \delta_j - \theta_{ij}) \quad (3)$$

$$V_{\min} \le V_i(S) \le V_{\max} \quad (4)$$

$$\omega_{\min} \le \omega \le \omega_{\max} \quad (5)$$

$$0 \le S_{gni}^{\max} - P_{gni}(S) \perp \frac{1}{k_{pi}} * (\omega_i^* - \omega) - P_{gni}(S) \ge 0 \quad (6)$$

$$0 \le Q_{gni}^{\max} - Q_{gni}(S) \perp \frac{1}{k_{qi}} * (|V_i^*| - |V_i|) - Q_{gni}(S) \ge 0 \quad (7)$$

$$S_{\min} \le S \le S_{\max} \quad (8)$$

where $S = (x_{DG}, x_k, x_{br})$ is the vector of optimization problem variables in which, x_{DG} is the bus number, representing DGs location,

$$x_{DG} = \left[bus_1^{dr} \ldots \quad bus_m^{dr}, bus_1^{PQ} \ldots \quad bus_m^{PQ}, bus_1^{Cap} \ldots \quad bus_m^{Cap}\right] \quad (9)$$

x_k represents static droop gains, frequency and voltage references,

$$x_k = \{\omega_i^*, |V_i^*|, s_{pi}, s_{qi}\} \quad i \in N_{dr} \quad (10)$$

and x_{br} is the cut-set lines of MG's clustering,

$$x_{br} = [branch_1, \ldots, branch_m] \quad (11)$$

Eq. (2) and (3) are equality constraints representing power balance conditions. Eqs. (4) and (5) are inequality constraints representing operational limits imposed on the system in terms of voltage magnitudes and system frequency, respectively. Eqs. (6) and (7) are complementary constraints meaning that the active and reactive power generation of the DG are based on droop controller operation. The notation $\perp$ in Eqs. (6) and (7) denotes a complement index. Eq. (8) shows the upper and lower limits of variables (see Eqs. (9)–(11)) involved in the optimization problem.

2.1. Objective functions

The description of the objective functions is given in the following, noting that such objective functions are normalized via dividing them by their base value.

2.1.1. Power losses

Following [23] the objective function related to power losses, per-unit (p.u.), can be calculated by,

$$f_1(S) = \sum_{i=1}^{N_{Br}} R_i I_i^2(S). \quad (12)$$

2.1.2. Voltage Stability Index (VSI)

Following [24] the objective function associated with VSI can be obtained by [24],

$$f_2(S) = \frac{1}{VSI(i+1)} \qquad i = 1, 2, \ldots, NB \; . \quad (13)$$

where

$$VSI_{i+1}(S) = V_i^4(S) - 4\left[\hat{P}_{i+1}(S) X_i - \hat{Q}_{i+1}(S) R_i\right]^2 - 4\left[\hat{P}_{i+1}(S) R_i + \hat{Q}_{i+1}(S) X_i\right]^2 V_i^2(S). \quad (14)$$

See Fig. 1 for the notation used in (14).

For the stable operation of MGs, VSI should be positive in each bus. Thus, for DGs installation, buses with low VSI values are good candidates since such buses of the MG are more likely to collapse.

2.1.3. Reliability (f_3)

The objective function related to the reliability improvement of MG is formulated based on increasing clustering ability of MGs. The ability of converting a MG to a number of self-adequate sub-MGs, those with minimum demand and generation unbalancing, is referred to as the clustering ability of MG. In doing so, it is required to identify the number of sub-MGs and a basis for clustering the MG. For the calculation ease it is assumed that the number of sub-MGs is given, for example based on the MG's configuration. A basis for MG's clustering in this paper is to identify lines with minimum load flow, called cut set lines, in which by disconnecting such lines self-adequate sub-MGs are formed. Mathematically the objective function associated with the clustering ability can be formulated as,

$$f_3(S) = \frac{\alpha \times P_{index}(S) + \beta \times Q_{index}(S)}{(N_{MGs} - 1)} \quad (15)$$

where P_{index} and Q_{index} represent the transmission total active and reactive power in cut-set line candidates, respectively, and they can be obtained by,

$$P_{index}(S) = \sum_{k=1}^{N_{MGs}-1} \left|P_{i,i+1}^k(S)\right| \quad (16)$$

$$Q_{index}(S) = \sum_{k=1}^{N_{MGs}-1} \left|Q_{i,i+1}^k(S)\right| \quad (17)$$

Notably, a value for f_3 equals zero or near zero implies that the total load of each sub-MG is supplied by its DGs.

It is acknowledged that a network can be considered radial or non-radial, this paper, solely focuses on radial types as majority of distribution networks are radial. Fig. 2 shows an example of clustering in an autonomous MG with three sub-MGs.

3. Optimization solution

To solve the above multi objective optimization problem a novel method is developed in order to find the optimal sizing and location of DGs and capacitances, droop parameters of DGs, and the virtual cut-set lines of sub-MGs. The development is based on a hybrid evolutionary algorithm, named HS-GA, which is a combination of the harmony search (HS) algorithm and the genetic algorithm (GA). A new load flow algorithm tailored to HS-GA algorithm is also presented.

It might be stressed that evolutionary algorithms (EAs) have different characteristics, advantages and disadvantages. In practice, EAs might be hybridized to deal with complicated optimization problems [25,26], this helps to increase advantages and reduce disadvantages of EAs [27–29]. Choosing an appropriate EAs hybrid method is vital in solving complex problems [29]. Typically, global search algorithms and local search algorithms or search operators of different algorithms are hybridized.

3.1. The HS-GA algorithm

HS is a new fast optimization method, proposed by [18], inspired by improving the process of musicians. This algorithm

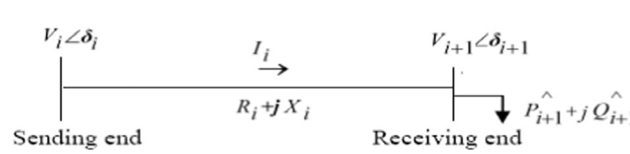

Fig.1. One-line diagram of MGs.

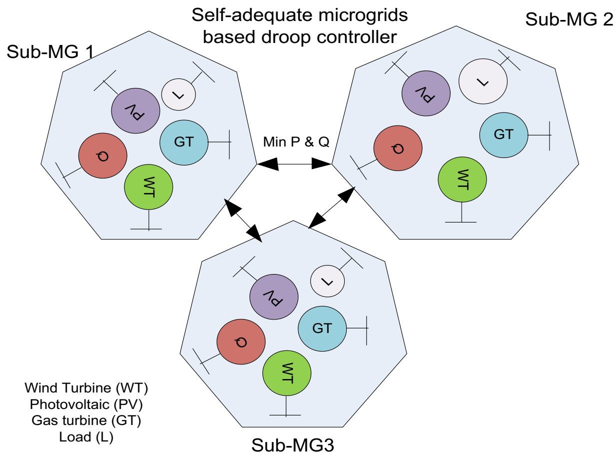

Fig. 2. An example of MG clustering.

uses decision parameters stochastically without any need for having initial values and it can efficiently handle interdependent relationships between decision parameters. The HS algorithm uses parameters such as harmony memory size (HMS), pitch adjusting rate (PAR), harmony memory considering rate (HMCR), and distance bandwidth (BW) for seeking answers in the problem space. Despite the fast response of HS there are however some limitations with the use of HS including low accuracy, sticking to local optimal solutions and failing to handle multi-objective problems.

Compared with HS, GA is a conventional optimization method which is frequently used in practice. However, low convergence speed and high calculation time are the main limitations that exist in GA. The proposed HS-GA is designed to overcome the limitations of both HS and GA. In addition, a fuzzy logic is added to HS-GA to find the best solution of the optimal objective functions from their set of Pareto front solutions.

The following outlines the main steps of HS-GA:

Step 1 (Initialization of HS): Set $t=0$ and generate solution vectors in the harmony memory (HM_1).

Step 2 (Load flow): Run the proposed load flow, discussed later, for each solution vector to determine power losses, VSI and power imbalance.

Step 3 (Fuzzy): Calculateμ_{f_1}, μ_{f_2} and μ_{f_3}, based on f_1, f_2 and f_3, as follows,

$$\mu_{f_i} = \begin{cases} 1 & f_i \geq f_i^{\min} \\ \frac{f_i^{\max} - f_i}{f_i^{\max} - f_i^{\min}} & f_i^{\min} \leq f_i \leq f_i^{\max} \\ 0 & f_i \leq f_i^{\max} \end{cases} \tag{18}$$

Step 4 (Fitness evaluation): Find the fitness function by,

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

where N_{POP} is the number of solutions in the harmony memory.

Step 5 (Time updating): update $t=t+1$.

Step 6 Generate a new harmony (x_{new}) in HM_1 according to the following sub-steps:

- Generate a random number (M) in the range [0, 1].
- If $M <$ HMCR, generate variable x_{newi} from the memory (HM_1).
- With a probability of PAR, modify x_{newi} by a small amount using (20).

$$x_{newi} = x_{newi} + M * BW \tag{20}$$

- If $M >$ HMCR, generate variable x_{newi} by a random choice of admissible region.
- If the fitness function, presented in (19), of the new harmony vector x_{new} is better than the worst harmony vector in HM_1, replace vector x_{new} with the worst harmony vector in HM_1.
- Save fitness of each vector in HM_1.
- Identify all the non-dominated answers and save them in the repository using Eqs. (21) and (22), as given, respectively,

$$f_n(x_1) \leq f_n(x_2) \qquad \forall n \in \{1, 2, ..., \tau\} \tag{21}$$

$$f_m(x_1) < f_m(x_2) \qquad \exists m \in \{1, 2, ..., \tau\} \tag{22}$$

It is stressed that the values of x_1 will dominate those of x_2 when Eqs. (21) and (22) are satisfied.

Step 7 (Initialization of GA): Generate harmonies for GA using HM_1 vectors as parents.

Step 8 Make new harmonies by the use of crossover and mutation operators of GA and then save them in HM_2.

Step 9 (Elitism): Generate a new harmony in HM_3 according to the following sub-steps:

- Merge HM_1 and HM_2.
- Run the load flow for HM_2.
- Determine the fitness of each objective function using the fuzzy method (18).
- Sort HM_2 vectors in a descending order of fitness values (19) and chose the best vectors for HM_3.

Step 10 Update HM_1 and the repository according to the following sub-steps:

- Swap the position of the harmony vectors in HM_1 with vectors found in HM_3
- Identify all the non-dominated answers and save them in the repository.

Step 11 (End) If a stopping criterion is met then end the calculation, otherwise go to Step 5.

Step 12 Select the non-dominated answers in the repository based on the harmony fitness degree (λ_μ^{Best}) given by,

$$\lambda_\mu^{Best}(n) = \frac{\sum_{i=1}^{N_{obj}} \kappa_i * \mu_{f_i}(x_n)}{\sum_{n=1}^{N_{Rep}} \sum_{i=1}^{N_{obj}} \kappa_i * \mu_{f_i}(x_n)} \tag{23}$$

Fig. 3 shows the flowchart of the proposed method.

4. Load flow algorithm in autonomous MGs

To calculate the objective functions in HS-GA a new load flow algorithm in the autonomous mode of MG needs to be run. This algorithm is developed here by considering that there is no slack bus in the autonomous mode, therefore DGs, which are based on droop controller, are required to participate in supplying loads to keep the MG frequency in its allowable range. In addition, DGs, such as WT, PV and battery, are treated as constant power sources [30,31]. The main steps of this algorithm are outlined as follows.

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1) *PQ Bus calculation*: The model of [32] is adapted to calculate the magnitude and phase angle of voltage for bus *j*, as given by,

$$V_j^2=\sqrt{\left(\left[rP_j+x(\omega).Q_j-\frac{V_i^2}{2}\right]^2-\left[r^2+x^2\right].\left[P_j^2+Q_j^2\right]\right)}-\left[rP_j+x(\omega).Q_j-\frac{V_i^2}{2}\right] \tag{24}$$

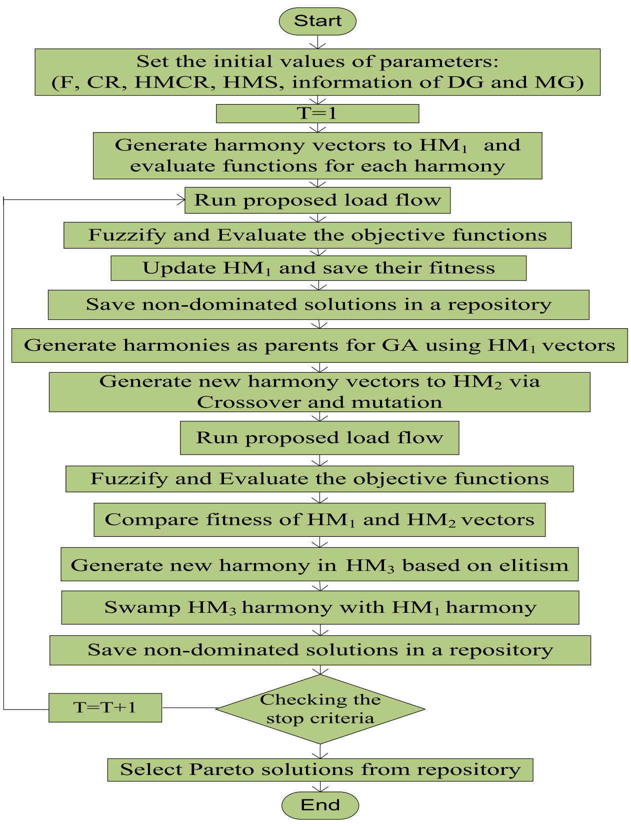

Fig. 3. Flowchart of the proposed method.

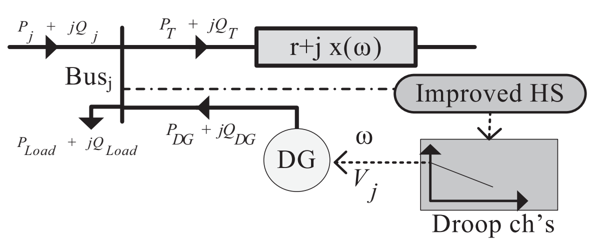

Fig. 4. Injected power from DG to bus *j* based on droop.

Table 1
HS-GA parameters.

HMS	Iteration	CR	BW	PAR	HMCR	F
20	30	0.33	0.01	0.45	0.8	0.55

Table 2
Maximum values for complex and reactive power of DGs in 69-bus MG.

No. DGs	S_{max} (MVA)	Q_{Max} (Mvar)
1	1.5	0.90
2	0.5	0.30
3	1.0	0.60
4	0.75	0.48
5	0.5	0.30
6	0.6	0.36
7	0.4	0.24

Table 3
Optimal DGs locations and cut-set lines.

Number of sub-MGs	DG location	Cut-set line location
2	49-54-64-59-57-10-45	41
3	62-17-50-54-43-2-27	17-35
4	61-41-5-9-18-62-11	12-35-9
5	63-10-49-64-13-2-24	3-6-11-15
6	62-2-58-11-22-49-38	4-35-9-16-60

Table 4
Values of objective functions of proposed method.

Number of sub-MGs	f_1	f_2	f_3
2	0.0181	1.0824	0.000
3	0.0197	1.0933	0.0972
4	0.0146	1.0955	0.1172
5	0.0085	1.0082	0.1262
6	0.0083	1.0098	0.5729

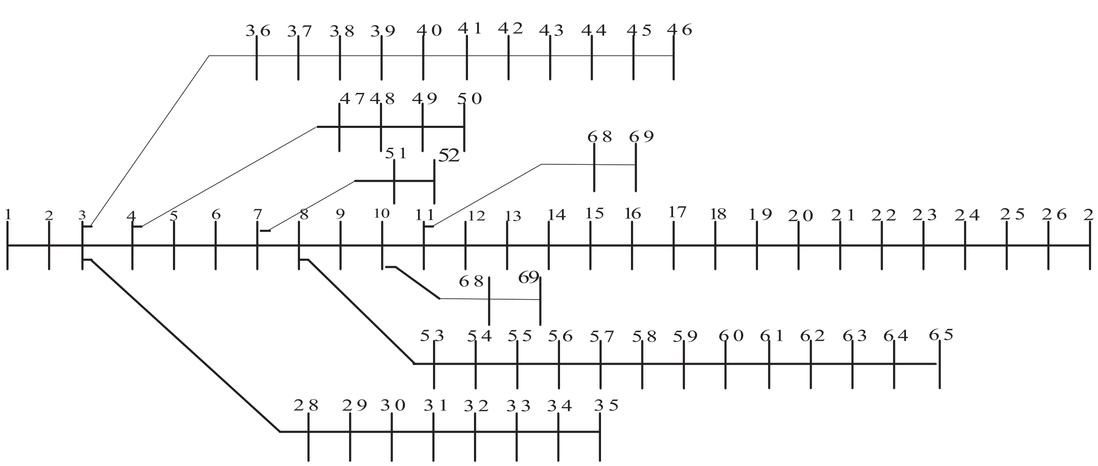

Fig. 5. 69-bus autonomous MG.

$$\delta_j = \delta_i - \sin^{-1}\left(\frac{x(\omega)P_j - rQ_j}{V_i V_j}\right) \tag{25}$$

2) *Droop Bus calculation*: Unknown variables of droop buses, as shown in Fig. 4, are considered as active and reactive power, and voltage magnitude and angle. To calculate the value of receiving end bus phase angle Eq. (25) is used where P_j and Q_j can be calculated, respectively, by,

$$P_j = -P_{DG} + P_{load} + P_T \tag{26}$$

$$Q_j = -Q_{DG} + Q_{load} + Q_T \tag{27}$$

Eqs. (26) and (27) are only applicable when the values of P_j and Q_j are within their allowed ranges. In the case where such values reach beyond their limits, P_j and Q_j are considered constant with values equal to their limits. In such cases the receiving end bus is converted from the droop control mode to the PQ mode. Therefore, the load flow problem needs to be resolved for the voltage phase angle and magnitude.

Table 5
Values of objective functions of pre-determined method.

Number of sub-MGs	f_1	f_2	f_3	DG location	Cut-set line location
6	0.0148	1.0184	0.5945	64-38-47-59-23- 3- 15	35-7-11-17-60

To calculate active and reactive power sharing based on the frequency and local voltage of each DG, Eqs. (28) and (29) are used, as given by,

$$P_{DGi} = \frac{1}{s_{pi}}(\omega_i^* - \omega) \tag{28}$$

$$Q_{DGi} = \frac{1}{s_{q_i}}(|V_i^*| - V_i) \tag{29}$$

5. Numerical results

Two case studies, 69 and 33 buses, based on autonomous operation, are assessed and simulated in MATLAB to evaluate the performance of the proposed method.

5.1. A 69-bus MG

The first case is a 69-bus MG, as shown in Fig. 5, including 68 lines, with maximum active and reactive loads of 3.8 MW and 2.69 MVar, and the MG nominal voltage of 12.66 kV [21]. Three scenarios are considered in this case. In the first scenario, it is assumed that DGs operate only based on droop controller, whereas in the second scenario, DGs are assumed to operate based on both droop controller and PQ buses (power constant). The assumption in the third scenario is similar to the second one, except that some capacitances are added to the MG for supplying reactive power. The tuning parameters used by HS-GA are given in Table 1.

Table 6
Values of droop control parameters of DGs for the case of 6 sub-MGs.

Scenario 1	Proposed method (HS-GA) (ω=0.99861)				PD method (ω=0.99801)			
DGs	S_p	S_q	V*	ω*	S_p	S_q	V*	ω*
1	3.3201E-5	2.541E-3	1.0071	0.99861	1.501E-3	0.0334	1.026	0.99989
2	5.1840E-5	3.510E-3	1.0000	0.99863	4.504E-3	0.1002	1.019	0.99911
3	1.7286E-3	0.014	1.0100	1.0000	2.252E-3	0.050	1.029	0.99999
4	1.9010E-5	5.32E-4	1.0018	0.99862	3.003E-3	0.0667	1.030	0.99974
5	2.0421E-4	1.78E-3	1.0001	0.99867	4.504E-3	0.1002	1.020	0.99906
6	2.4860E-4	0.0123	0.9970	0.99869	3.753E-3	0.0835	1.019	0.99915
7	5.8823E-3	1.61E-3	1.0002	1.0000	5.63E-3	0.1253	1.031	0.99977

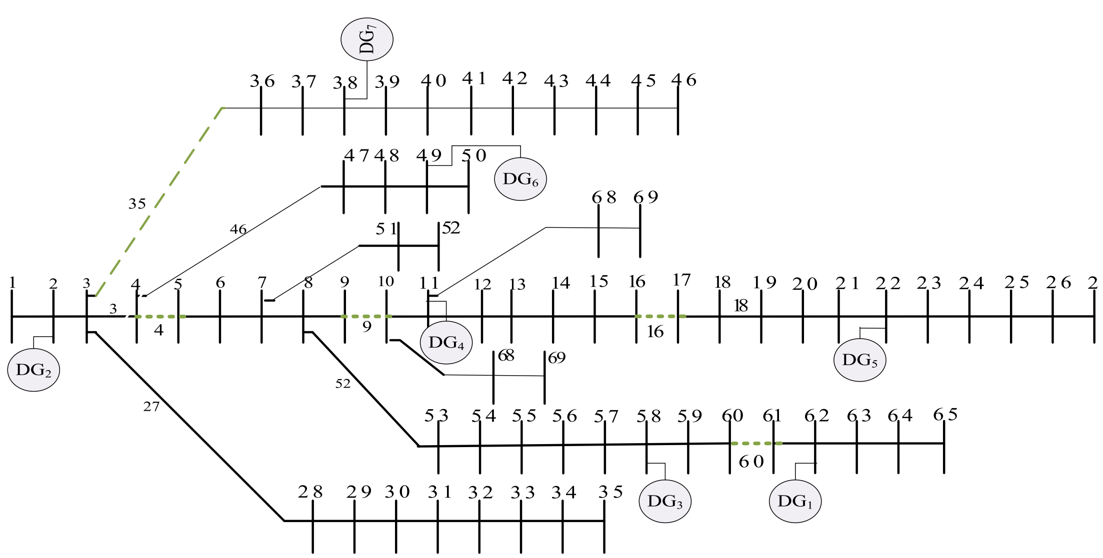

Fig. 6. Optimal locations of DGs and cut-set lines (dash lines) for the case of 6 sub-MGs (Scenario 1).

Scenario 1: *MGs with only droop controllers*

In this scenario 7 DGs, operating based on droop controller, are considered and the performance of the proposed method (with tuning of droop parameters) is compared with a method where droop parameters are fixed (without tuning); this is called here pre-determined (PD). For the PD method it is assumed that the allowable frequency and voltage deviation are equal to 0.5% and 5% of their nominal values, respectively. Also, the values of ω^* and V^* are assumed to be determined based on satisfying power demands and security conditions of MGs. Table 2 gives power specifications of the DGs.

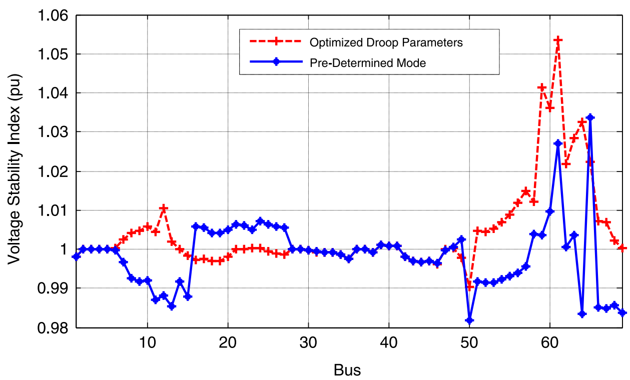

Fig. 7. VSI in autonomous MG.

Table 7
Power generated, demand and losses for 69-bus system (*P* (MW), *Q* (MVAR)).

Methods	P_{DG}	P_D	Q_D	Q_{DG}	P_{Loss}	Q_{loss}
Proposed method (HS-GA)	3.7797	3.7722	2.6941	2.6992	0.0081	0.0053
PD	3.7833	3.7722	2.6941	2.7057	0.0148	0.0116

Table 8
Optimal locations of DGs and cut-set lines (the first three DGs are PQ based and others are droop controller based).

Number of sub-MGs	DG location	Cut-set line location
2	50-11-14-61-62-2-64-36	35
3	9-44-48-62-17-2-61-64	6-53
4	65-41-24-62-7-4-63-10	12-54-9
5	42-64-48-62-14-7-61-11	7-53-11-3
6	6-50-12-62-61-46-20-63	3-7-13-9-62

Table 3 illustrates the optimal DGs locations and cut set lines for different number of sub-MGs, Table 4 summarizes the values of objective functions provided by the proposed method and Table 5 gives the values of such functions calculated by the PD method when the number of sub-MGs is 6. Table 5 demonstrates that by converting the MG to two sub-MGs the preferred alternative is obtained as the values of MG losses and voltage stability index (f_1 and f_2) are the lowest and the value of load flow of the cut-set line (f_3) is zero. Table 5 also shows that by increasing the number of cut-set lines (sub-MGs) the values of objective functions are raised.

Table 6 compares the values of droop parameters obtained by the proposed method with those of the PD method when the MG is converted to six sub-MGs and Fig. 6 graphically shows the optimal location of DGs and cut set lines. Fig.7, comparing VSI calculated by the proposed method (optimizing droop parameters) and the PD method, demonstrates that the performance of the proposed method is effective in improving VSI.

Table 7 shows generated, demand and losses of active and reactive power of the proposed method and the PD method. This table illustrates that the values of power losses and subsequently power calculated by the proposed method are less than those of the PD method. This provides support for the effectiveness of the proposed method.

Scenario 2: *MGs with droop controllers and PQ Buses*

In this scenario, five DGs based on droop controller along with three DGs based on PQ operation are examined. Power specifications of DGs based on droop controller are similar to those of DG_3 to DG_7, given in Table 1. For DGs based on PQ operation the maximum capacity is considered 565 KW at 0.8 power factor.

Table 8 illustrates the optimal DGs locations and cut set lines for different numbers of sub-MGs and Fig. 8 shows this graphically (for the case of 6 sub-MGs).

The values of objective functions provided by the proposed method are summarized in Table 9. This table shows that with increasing the number of sub-MGs the values of objective function increases.

A comparison between Tables 4 and 9 reveals that MGs designed based on both droop controllers and PQ (Scenario 2) are more effective than MGs with only droop controllers DGs (Scenario 1). This implies that in circumstances when a fault happens in the MG, systems designed based on Scenario 2 are more reliable compared with those designed based on Scenario 1.

The values of droop control parameters of DGs, provided by the proposed method, are summarized in Table 10.

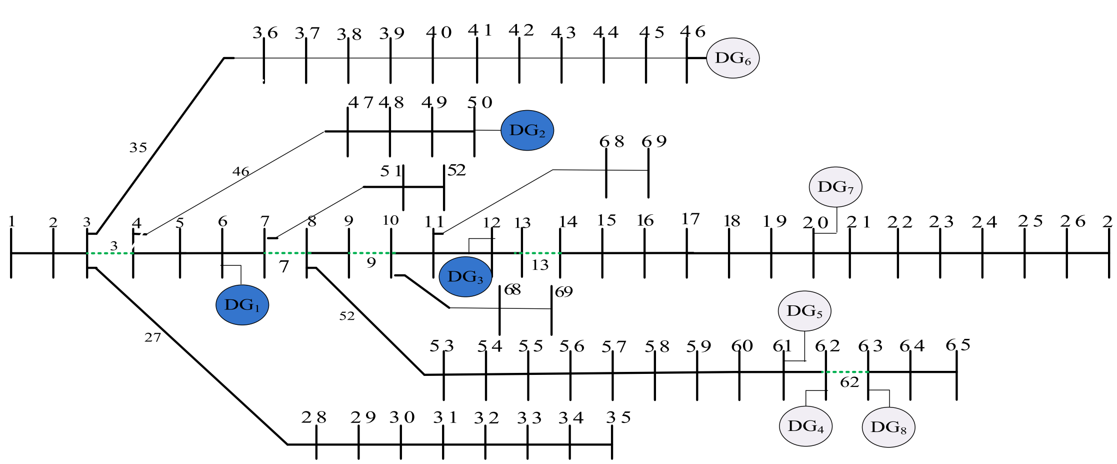

Fig. 8. Optimal locations of DGs and cut-set lines (dash lines) for the case of 6 sub-MGs; PQ buses are in blue and droop buses are in grey.

Scenario 3: MGs with droop controllers, PQ Buses and capacitances

In this scenario the configuration of the MG is similar to Scenario 2, except that three capacitances with total capacity of 120 kVar are added to the system. The corresponding results for optimal locations of DGs and cut set lines of different numbers of sub-MGs are illustrated in Table 11 and for the 6 sub-MGs case is graphically shown in Fig. 9.

Table 12 summarizes the associated values of objective functions. A comparison between Tables 4, 9 and 12 reveals that the lowest values of the objective functions correspond to the third scenario. This demonstrates that the use of capacitances in sub-MGs is beneficial in improving the operation of MGs. In addition, such comparison for the values of f_3 demonstrates that lowest value of the reactive power imbalance belongs to the third scenario, illustrating another benefit of the use of capacitances. For this scenario the optimized droop controller parameters of DGs, obtained by the proposed method, are shown in Table 13.

Fig. 10 compares voltage profile values for the 69-bus system with DGs (the above three scenarios) and the 69-bus system without DGs and capacitances where a substation is employed for providing loads. Fig. 10 demonstrates that ignoring DGs and capacitances in the system leads to a reduction in voltage profile values, especially in bus 65. Fortunately, Fig. 10 shows that such reduction can be improved with the installation of DGs and particularly the simultaneous use of both DGs and capacitances.

Table 14 summarizes the corresponding results, provided by the proposed method, for f_1, f_2, f_3 and reactive power losses in each scenario.

Table 14 shows that with increasing the number of DGs, the ability of sub-MGs in supplying their loads are raised. This table also shows that, comparing with other scenarios, the active and reactive power losses in the third scenario are reduced. In addition, Table 14 illustrates that an increase in the load flow of cut set lines in sub-MGs follows from a rise in the number of sub-MGs, though this rise in the third scenario is lower than other scenarios. Moreover, Table 14 demonstrates an improvement in the voltage

Table 9
Values of objective functions.

Number of sub-MGs	f_1	f_2	f_3
2	0.0055	1.0230	0.0000
3	0.0066	1.0163	0.0566
4	0.0093	1.0186	0.0919
5	0.0082	1.0159	0.1166
6	0.0078	1.0171	0.3985

Table 10
Values of droop control parameters of DGs (Scenario 2).

Scenario 2	HS-GA (ω=0.99807)			
DGs	S_p	S_q	V^*	ω^*
1	1.1293E-3	5.134E-3	1.0110	0.99903
2	3.6463E-3	0.0034	1.0225	1.0004
3	1.48436E-3	0.0579	1.0200	0.99861
4	4.61612E-3	0.0277	1.0150	1.0000
5	5.68676E-3	0.01125	1.0107	0.9999

Table 11
Optimal locations of DGs and cut-set lines.

Number of sub-MGs	DG location	Cut-set line location	Capacitance location
2	18-60-49-63-36-7-11-61	51	21-40-26
3	37-28-7-61-62-60-12-20	7-15	39-14-52
4	6-63-21-61-50-62-2-11	4-9-52	47-42-54
5	60-50-40-62-6-11-17-61	8-55-12-3	59-63-26
6	2-11-4-61-62-38-64-22	16-62-9-4-35	49-16-12

Table 12
Values of objective functions.

Number of sub-MGs	f_1	f_2	f_3
2	0.0044	1.0156	0.0000
3	0.0057	1.0187	0.0104
4	0.0027	1.0160	0.0822
5	0.0038	1.0111	0.1056
6	0.0060	1.0170	0.2753

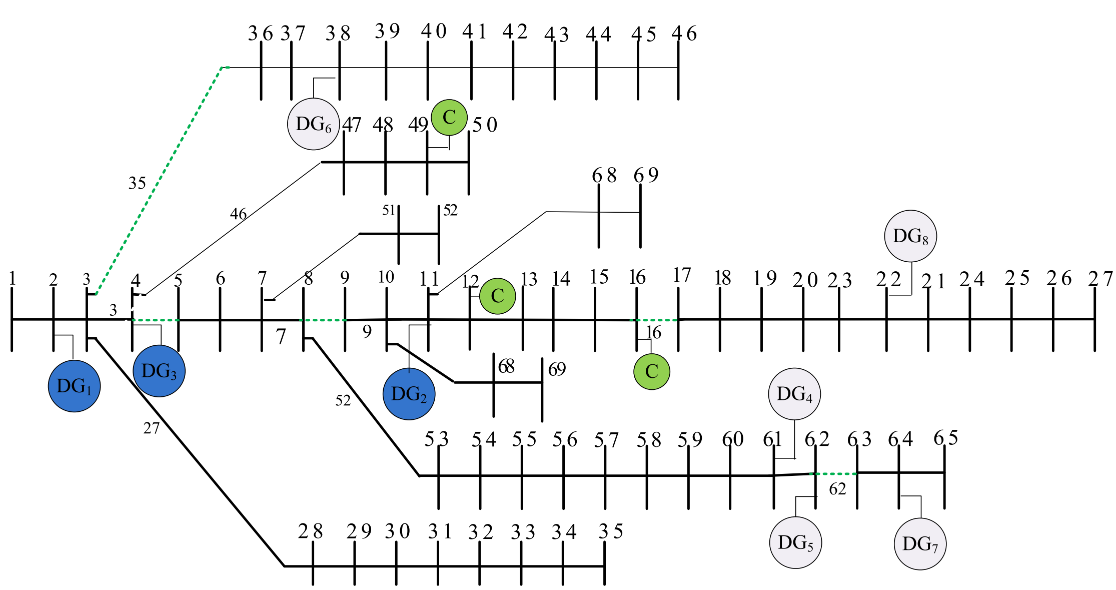

Fig. 9. Optimal locations of DGs and cut-set lines for the case of 6 sub-MGs (Scenario 3).

stability index in the third scenario. Finally, the results for Scenarios 2 and 3 demonstrate that DGs based on PQ are located in regions with low load values and DGs based on droop controller are, however, located in regions with high load values. Such MGs clustering assists in minimizing load outage values in the system when any disturbance occurs in sub-MGs.

In order to show the ability of the proposed optimization method, HS-GA, a comparison between its performance and those of other optimization techniques (PSO, GA, HS and PDE) for 50 runs of their algorithms, in Scenario 3, are made. The date used for PSO and PDE techniques are based on [24] and [21], respectively. Three criteria, standard deviation (SD), best mean (BM) and worst value (WV), are utilized to make such comparison [33]. The BM criterion shows the ability of convergence of an algorithm while the SD criterion illustrates the stability of an algorithm. The corresponding results are summarized in Table 15. Table 15 shows that HS-GA provides the lowest values for SD and BM compared with PDE and PSO. This proves the effectiveness of HS-GA.

To provide further support for the performance of HS-GA, the results provided by HS-GA are compared with those available in the relevant literature [33–35] and [21]. The associated results are given in Table 16. This table illustrates that the values of active and reactive power losses and VSI provided by HS-GA are in general lower than those provided in the literature, demonstrating the effectiveness of HS-GA.

Table 13
Values of droop control parameters of DGs (Scenario 3).

Scenario 3	HS-GA (ω=0.99903)			
DGs	S_p	S_q	V^*	ω^*
1	9.4817E-4	1.5029E-3	1.0091	0.99978
2	1.9334E-4	3.3465E-3	1.0106	0.99917
3	5.4201E-5	1.4409E-3	1.0007	0.99905
4	2.7196E-5	0.02138	1.0161	0.99904
5	3.6075E-3	8.0160E-3	1.0000	1.0001

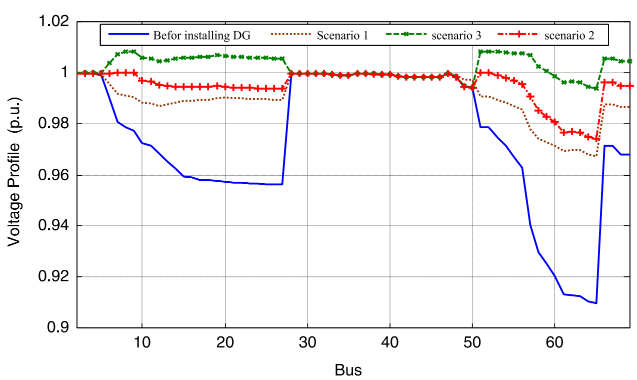

Fig. 10. Voltage profile of 69-bus system for different situations.

Table 14
Results of proposed method in each scenario.

Cases	Objective Functions (p.u.)			
	Active power losses (f_1)	Reactive power losses	VSI (f_2)	Power imbalance (f_3)
Without installing DGs	0.222	0.1008	1.45	–
Scenario 1	0.0083	0.0094	1.0098	0.5729
Scenario 2	0.0078	0.0087	1.0171	0.3985
Scenario 3	0.0060	0.0071	1.0177	0.2753

5.2. A 33-bus MG

The second case study is a 33-bus MG, as shown in Fig. 11, with 32 lines and maximum active and reactive loads of 3.715 MW and 2.30 MVar, and the MG nominal voltage of 12.66 kV [17]. Four DGs, (DG_1–DG_4 in Table 2) along with three capacitances with 80kVar are used. It is assumed that the 33-bus MG is converted to 4 sub-MGs. Table 17, comparing the calculation results of HS-GA with those of PDE [21], PSO [11] and GA, shows the effectiveness of HS-GA.

Table 18 shows the required calculation time of different methods in Scenario 3 for 50 runs. This table demonstrates that the proposed method is fast in calculating the results for the both case studies.

Table 16
Comparison of performance of HS-GA with other methods.

Methods	Objective functions (p.u.)		
	Active power losses	Reactive power loss	VSI
HS-GA	0.0060	0.00710	1.0177
PDE [21]	0.0810	0.06250	1.0294
IMOHS [33]	0.0128	0.00927	1.0142
Analytical [35]	0.0702	0.03230	1.0269
PSO [34]	0.0760	0.05300	1.0262

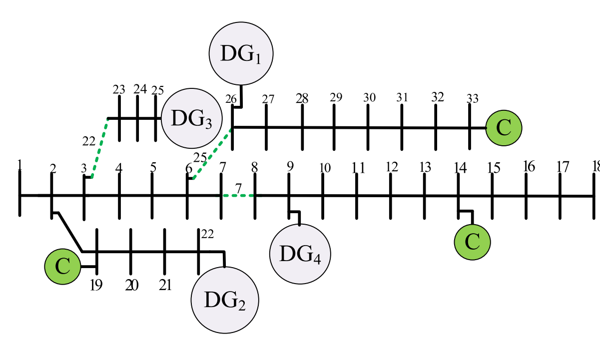

Fig. 11. Optimal locations of DGs and cut-set lines in 33-bus system.

Table 15
Results of SD, BM and WV for HS- GA, PSO, GA, HS and PDE (Scenario 3).

	HS-GA			PSO			PDE [21]			HS			GA		
	SD (%)	BM	WV	SD (%)	BM	WV	SD (%)	BM	WV	SD (%)	BM	WV	SD (%)	BM	WV
f_1	1.48	0.007	0.009	1.82	0.016	0.058	1.52	0.008	0.016	1.72	0.021	0.063	1.58	0.012	0.083
f_2	1.63	1.025	1.173	1.94	1.041	1.182	1.81	1.021	1.194	1.84	1.051	1.862	1.74	1.033	1.946
f_3	1.72	0.291	0.301	2.15	0.317	0.459	1.94	0.303	0.406	2.03	0.321	0.486	1.97	0.306	0.501

Table 17
Comparison of performance of HS-GA with other methods in 33-bus system.

Methods	DG location	Cut-set line location	Capacitance location	f_1	f_2	f_3
HS-GA	25-22-26-9	22-25-7	33-14-19	0.0041	1.0419	0.0615
PDE [21]	26-6-18-23	10-25-22	30-16-3	0.0073	1.0375	0.0749
GA	30-6-18-10	11-27-6	9-33-20	0.0116	1.0583	0.0835
PSO [11]	16-20-27-6	10-3-26	15-5-26	0.0094	1.0406	0.0588
HS	11-18-26-21	14-25-4	30-12-21	0.0047	1.0558	0.0842

Table 18
Calculation time in Scenario 3 for 50 runs.

MGs	Average time (min)				
	HS-GA	PDE [21]	GA	Improved PSO [11]	HS
69-Buses	11.0518	15.7310	19.0714	14.3824	17.5537
33-Buses	7.1150	10.3814	12.4025	9.1047	11.0612

6. Conclusion

A novel method for addressing technical and reliability problems of MGs based on converting the MG to a number of self-adequate autonomous sub-MGs via adopting MGs clustering thinking is proposed. In order to design self-adequacy sub-MGs, an optimization problem, including three objectives, power losses reduction, voltage profile improvement and reliability enhancement are formulated. To solve the optimization problem a hybrid algorithm, HS-GA, is provided, based on improving the HS algorithm via using GA operators in order to increase convergence speed and improve optimal solutions. The results show that HS-GA can effectively handle interdependent relationships between the decision variables. Two case studies and three scenarios were assessed to show the performance of the proposed method. The results provide support for the performance of the proposed method. The results also show that the use of DGs, based on both droop controllers and PQ, along with capacitances improves the performance of MGs. It can be concluded that the proposed algorithm can be served as an effective tool for designing autonomous sub-MGs in smart networks.

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