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Optimal Allocation for Combined Heat and Power System with Respect to Maximum Allowable Capacity for Reduced Losses and Improved Voltage Profile and Reliability of Microgrids Considering Loading Condition

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Abstract

This paper presents a method that uses particle swarm optimisation to select the optimal allocation of a combined heat and power system that considers the maximum allowable capacity with the aim of reducing losses, improving the voltage profile and reliability of microgrids considering networks loading condition. Decision variables are optimal location and capacity of the combined heat and power systems. The location and maximum capacity of the combined heat and power system were specified in a way to reduce losses, improve the voltage profile, reliability improvement as energy not supplied reduction and maintain the operating constraints. The method is applied to 84- and 32-bus standard microgrids. Capability of the proposed method is proved in obtained results which demonstrated a significant enhancement in voltage profile and a decrease in power losses and customer's energy not supplied as reliability improvement. Minimum microgrid losses can be achieved with considering these constraints. The power loss, minimum voltage and reliability is improved 43.9%, 3,4% and 80.31% for 84 bus network and 72%, 6.2% and 83.6% for 32 us network, respectively by optimal combined heat and power systems allocation. Also, the superiority of the particle swarm optimization is confirmed in comparison with the genetic algorithm.

Keywords: Microgrid, Loss reduction, Maximum allowable, combined heat and power, Improving voltage profile, Reliability, Particle swarm optimisation.

Nomenclature

Acronyms		F	Objective function
CHP	Combined-Heat-and-Power	**Variables**	
DER	Distributed Energy Resource	P_{ij}^{Line}	Distribution line Power
DG	Distributed Generation	$P_{ij,max}^{Line}$	Line Thermal limit
MG	Microgrid	S_{CHPG}	Size of CHPG
PSO	Particle Swarm Optimization	$P_{max,w,i}$	Maximum authorized power
WT	Wind Turbine	$P_{min,w,i}$	Minimum authorized power
ENS	Energy Not Supplied	P_i	Injected active powers
C	Power factors between two community	Q_i	Injected reactive powers
I	Current	$v_i(t)$	Optimizing the particle velocity
k	Line number	$L_{f,i}$	Feeder *i* domain
P	Power	$L_{f,i}^{max}$	Feeder *i* maximum current
S	Dimensional vector	N_{bus}	Number of buses
X	Line reactance	N_f	Number of feeders
Functions		R	Line resistance
P_{loss}	Line losses	**Sets**	
P_{CHPG}	Power of the Combined-Heat-and-Power generated	V_i	Bus *i* voltage
δ_i	Bus *i* Angle voltage	V_m	Voltage domain
V_{ij}	The domain between the bus *i* and *j*	t	Time
θ_{ij}	Admittance angle between bus *i* and *j*	t_{max}	Maximum time

1. Introduction

Everyday human activities generate greenhouse gases, which are the primary causes of global warming, along with increased carbon dioxide emissions. The use of distributed energy resources (DERs), e.g., wind turbines and combined heat and power (CHP) systems can resolve this issue. A CHP system is a small electric generation plant capable of providing power for industrial facilities, commercial facilities, and household applications; therefore, it has been widely used in microgrids (MGs) [1]. MG refers to a network that supplies power in a small scale, which consists of intermittent sources such as DERs and controllable sources such as CHP systems; moreover, MG can be employed at distribution level [2]. The primary responsibility of an MG is to provide reliable and quality power through decentralised electricity generation, combined with the on-site production of heat for its consumers at an economical cost [3]. However, it can be a challenging task to ensure a consistent connection between the DER and MG. Power generation using a CHP system has advantages such as increased system reliability, reduced MG power losses, improved voltage profile, peak load shaving and accelerated transport on the transmitting and distributing lines of MG [4]. If important factors such as the location, number, and/or capacity of the CHP system are selected incorrectly, it can result in power loss and voltage deviation, which are major MG problems. Thus, it is of a high importance to specify the optimal location and amount of fuel for the CHP system. To achieve this goal, it is necessary to consider several limitations.

All of the control methods that have been proposed in the literature for decentralized control of distributed energy resources in MG must compute the power level in a way to make an effective decision whether the generated power is capable of stabilizing the system [5]–[8]. The two-degree displacement method for positioning a distributed generation (DG) system was introduced in [9]. Based on this study, the generation of energy closer to the load will diminish the need for power lines of long distances; further, several studies were carried out to specify the most appropriate location for a CHP system using optimisation methods [10]. The methods in [1] and [11] were introduced to literature to specify the best status of efficiency and the most appropriate size of a CHP system for customers through taking into consideration a unified view of electricity on the basis of the new concept of energy hubs. In [12], a methodology was proposed for modelling on-site energy generation systems. This has made it easy to integrate the transient efficiency of the energy supply machines at partial loads. In [13], a planning model that included energy balances and constraints for system control and operation was built, and an efficient algorithm to minimise the overall costs of the net acquisition for the heat and power of the CHP system was developed. Basu et al. [14] proposed a cost-benefit analysis method to improve the reliability of both 6- and 14-bus meshes as well as radial MGs. Hence, various costs and benefits related to the extension of a CHP system for an economic feasibility study were considered. Safaei et al. [15] proposed a new algorithm based on particle swarm optimisation (PSO) that was working in two steps in order to allow the WT generators placement while bearing in mind their maximum allowable capacity. In the present research, the control variables were obtained, and the maximum WT output varied with the optimised control variables on the basis of the minimisation of power losses. Another study [16] determined the optimal value of the DG capacity that could be connected to the existing system using PSO to maximise the power quality. Furthermore, an analysis was done on the benefits of utilizing DG with the help of two indices: a line loss reduction and a voltage profile improvement. In [17], optimal placement of the DG units in the MG are determined optimally. In [18], the desired installation location and size of the DG unit. The assessment of the maximum permissible DG capacity was performed using a dual genetic algorithm approach [19]. The CHP system is one of the DERs that can produce electricity in remote and difficult zones where MG power is unavailable [20-21]. However, certain disadvantages may occur while integrating CHP systems with the MG if the capacity and position of the CHP system are not appropriate.

In this paper, optimal allocation for CHP system is proposed with respect to maximum allowable capacity with objective of power losses reduction and voltage profile and reliability improvement of MGs. The optimal location and size of CHPs as decision variables are determined optimally using two step approach based on PSO algorithm. The proposed method is done on 84 and 32-bus

MGs. The simulation results are compared in different scenarios in view of power loss, minimum voltage, maximum voltage, voltage profile before and after optimization considering a different number of CHPs. Also, the performance of the PSO is evaluated in comparison with genetic algorithm (GA) in problem solving.

The highlights of the manuscript are as follow:

- CHP optimal allocation in microgrids using two-stage particle swarm optimization
- Multi-objective function include loss and voltage deviation reduction and reliability improvement
- CHP optimal allocation considering variable loading profile
- Performance evaluation of PSO compared with GA

The rest of this paper is organized as follows: In section 2, the modelling of the generating units is presented. In section 2, the statement of the problem includes objective function and constraint is described. The solution method is defined in section 4. Simulation results and discussions are presented in section 5. Finally, the results are concluded in section 6.

2. Modelling of generating units

Fig. 1 illustrates the graphical abstract of CHP, thermal, and heat unit allocation based on a multi-objective problem using PSO. Waste heat utilisation by the CHP technologies is one of the key economic and environmental components because the generated electricity increases the plant efficiency. A CHP unit can generate heat and power and should be operated in a practical region.

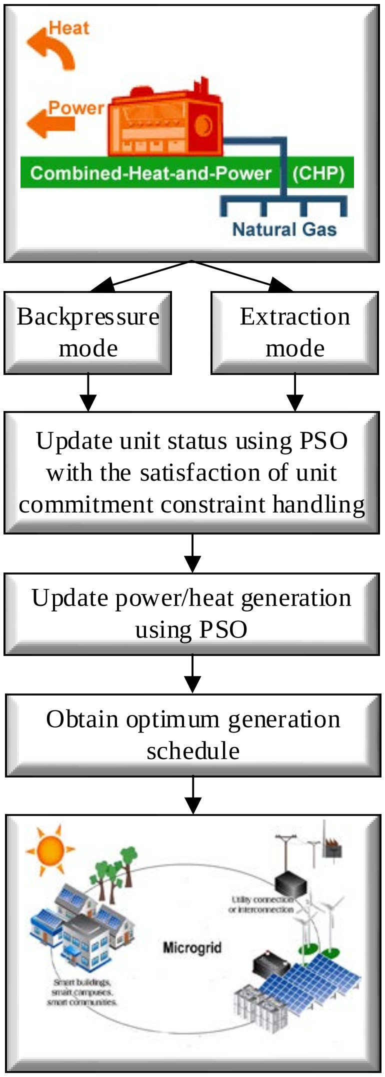

Fig. 1. Graphical abstract of multi-objective CHP problem using PSO.

Equations (1) and (2) give the appropriate limits of the heat and power generation of the CHP plants [21]:

$$\underline{P_j}(H_j) \leq P_{tj} \leq \overline{P_j}(H_j) \quad t\forall T, \qquad j\forall N_c \tag{1}$$

$$\underline{H_j}(P_j) \leq H_{tj} \leq \overline{H_j}(P_j) \quad t\forall T, \qquad j\forall N_c \tag{2}$$

3. Statement of problem

3.1. Objective function

In the present paper, the objective functions for selecting locations for installing CHP systems in an MG were considered to minimise the losses and improve the voltage profile and reliability. The total objective function is considered as a weighted coefficient method.

The objective function for minimising active power losses is expressed as follows [15]:

$$F_1 = P_{loss} = \sum\nolimits_{t=1}^{T} \sum_{k=1}^{N_{br}} R_k I_k^2 \tag{3}$$

$$I_k = \left| \frac{V_n - V_m}{R_k + jX_k} \right| \tag{4}$$

where k stands for the line number between buses i and j; R and X represent the line resistance and reactance, V_m and V_n refer to voltage of bus m and n, respectively; I denote the current passing through the line; and P_{loss} signifies the line losses. T refers to duration study.

The objective function for the improvement of the voltage profile is defined in Equation (5):

$$F_2 = \sum\nolimits_{t=1}^{T} \sum_{l=1}^{N_{bus}} |V_l - 1| \tag{5}$$

where, V_l denotes the voltage of l^{th} bus and N_{bus} signifies the number of buses in MG.

The objective function for the improvement of the network reliability to reduce energy not supplied of customers based on the basic indices of the load point and energy consumption at load points, energy not-supplied (ENS) (kWh/year) is calculated as follows [15]:

$$F_3 = \sum\nolimits_{t=1}^{T} \sum_{i=1}^{nl} \lambda_{a(j)} u_j \tag{6}$$

where nl represents the total number of load points, $\lambda_{a(j)}$ is the unavailability of the load point j (hours / year), and u_j is the average load connected at the load point j (kW).

In this paper, the optimisation variables included the location for the CHP system and its size in MG. In the decision vector X, there are two separate sections. The first one, P_{CHPG}, depicts the installation location of the generation unit of the CHP system in MG, while the second one is the size of the CHP system, S_{CHPG} [15]:

$$X = [P_{CHPG} \;\; S_{CHPG}] \tag{7}$$

3.2. Constraints

The optimization of the problem's objective function was done with the following constraints:

- *Power of distribution line in MG*

$$\left| P_{ij}^{Line} \right| < P_{ij,max}^{Line} \tag{8}$$

where P_{ij}^{Line} represents the power of the line and $P_{ij,\max}^{Line}$ stands for the thermal limit of the line.

- *Power flow equations*

$$P_i = \sum_{i=1}^{N_{bus}} V_i V_j Y_{ij} \cos\left(\theta_{ij} - \delta_i + \delta_j\right),\ Q_i = \sum_{i=1}^{N_{bus}} V_i V_j Y_{ij} \operatorname{Sin}\left(\theta_{ij} - \delta_i + \delta_j\right) \tag{9}$$

where, P_i and Q_i signify the injected active and reactive powers, respectively, and V_i and δ_i denote the voltage domain and angle of bus i, respectively. Y_{ij} and θ_{ij} stand for the amplitude and angle of branch admittance between bus i and bus j, respectively.

- *Loading of lines*

$$\left|L_{f,i}\right| < L_{f,i}^{max} \quad i = 1,2,\dots,N_f \tag{10}$$

where N_f shows the number of existing feeders and $L_{f,i}$ and $L_{f,i}^{\max}$ represent the domain and maximum current of feeder i, respectively.

- *Maximum active power of CHP*

$$P_{min,w,i} \le P_{w,i} \le P_{max,w,i} \tag{11}$$

where, P_{min}, w, i and P_{max}, w, i denote the minimum and maximum values of the authorised power of CHPG i, respectively.

- *Bus voltage*

$$V_{min} \le V_i \le V_{max} \tag{12}$$

where, V_{min} and V_{max} signify the minimum and maximum bus voltages, respectively.

4. Solution method

4.1. Particle swarm optimisation

PSO is known generally as an influential method that can be effectively applied to the solution of optimisation problems. It has been confirmed in the literature to have high levels of accuracy and convergence speed in power system research. PSO, pioneered by Kennedy and Eberhart in 1995 [22], is indeed derived from the group movements of birds and fish looking for food. Some types of animals, particularly fishes and birds, always travel within groups with no contact with each other. Each member follows its own group and constantly fine-tunes its position and speed with the help of the information available to the group. This (searching as a group) reduces the individual labour (individual searching) needed to obtain food and shelter. The PSO and genetic algorithms are similar because they are both population-based algorithms [23]. However, PSO has a computational advantage because it requires less computing space (memory), CPU speed, and parameters for adjustment.

In the basic PSO algorithm, swarm refers to the whole population, and particle refers to each member of the population. Movement of particles is done within an n-dimensional search space (n denotes the number of optimisation variables). Within this system, each particle may represent a probable answer to the optimisation problem in hand. Remember that only the velocity and position of each particle introduce the particle; as a result, Equation (13) can express the mathematical model of this algorithm [13]:

$$S_i(t) = \left(S_{i,1}(t), S_{i,2}(t), \dots, S_{i,n}(t)\right) \tag{13}$$

where, S stands for an n-dimensional vector that represents the position of element i at iteration t, and n signifies the number of optimisation variables. For instance, $S_{i,1}(t)$ shows the state (value) of the first optimisation dimension (the first variable) of particle i at iteration t. Each particle's velocity at t is expressed by Equation [22]. In particular, Equation (14) shows the velocity that is required to change an element position. For instance, $V_{i,1}(t)$ signifies the velocity of optimising particle i to the first dimension (first variable) at t:

$$V_i(t) = \left(V_{i,1}(t), V_{i,2}(t), \dots, V_{i,n}(t)\right) \tag{14}$$

Initially, the creation of particles is done with random velocities and positions; After that, on the basis of Equations (16) and (17), updating of each particle is done by means of the two best values [22]:

$$P_i(t) = \left(P_{i,1}(t), P_{i,2}(t), \dots, P_{i,n}(t)\right) \tag{15}$$

$$P_{gb}(t) = \left(S_{gb,1}(t), S_{gb,2}(t), \dots, S_{gb,n}(t)\right) \tag{16}$$

where P stands for an n-dimensional vector showing a particle's optimum position until iteration t. P_{gb} represents an n-dimensional vector demonstrating the optimum position within the whole community until t (the optimum position for one of the particles within the group). Remember that $P_i(t)$ and $P_{gb}(t)$ are updated in each period, t. Equations (17) and (18) define the changes that occur at iteration t+1 (changes in the position and rate of the position change of each particle). When processing this algorithm and during each iteration of the process, each member has to remember its best position and the best position within the whole community. Each member changes its position on the basis of the two positions in the following equations:

$$S_i(t+1) = k\left[w(t)(t)S_i(t) + C_1 rand_1(P_i(t) - S_i(t)) + C_2 rand_2\left(P_{gb}(t) - S_i(t)\right)\right] \tag{17}$$

$$S_i(t+1) = S_i(t) + V_i(t+1) \tag{18}$$

In equation (17), C_1 and C_2 represent the power factors between two communities and individual forces. That is, the larger value of coefficient C_1 relative to C_2, the impact of individual less than the swarm and more it acts individually and for fewer values, more it affects the swarm. The elements are not all comparable; as a result, in a real community, the factors differ. The variable

$w(t)$ represents inertia, i.e., not having any tendency for changing the path, in a particle, and rand_1 and rand_2 represent the random numbers uniformly distributed in the interval of 0-1. Equation (18) indicates that when a particle is moving, it takes into consideration the best position experienced in the former movement and also considers the best position for the whole group. In Equation (17), coefficient k is utilized in order to make sure of convergence, and it is defined as expressed in Equation (19). When k = 0.75, such convergence can be ensured. On the basis of the way the coefficients are defined, C_1 and C_2, and w are formed in various versions of PSO. The factor, $w(t)$, controls the variety and diversity of exploration (for the purpose of obtaining various probable solutions within the problem space) and convergence of particles. For the avoidance of divergence, elements should be capable of searching the space with smaller steps over the iteration; as a result, in an enhanced version of PSO method in each iteration, each coefficient w is changed. This parameter is initially fixed at the largest value of w_{max} in a way to enlarge the exploration scope within the problem space. After that, to attain an answer of higher accuracy, the parameter is reduced in a linear way (with a constant gradient) until it reaches w_{min} in the last iteration. For each iteration, Equation (20) is used to calculate its size [22]:

$$k = \frac{2}{\left|2 - \varphi - \sqrt{\varphi^2 - 4\varphi}\right|}, \varphi = C_1 + C_2, \varphi \geq 4 \tag{19}$$

$$w(t) = w_{max} - \frac{w_{max} - w_{min}}{t_{max}} t \tag{20}$$

In equation (20), t_{max} stands for the maximum iteration and t denotes the number of iterations performed simultaneously.

4.2. Proposed method implementation

The proposed method involves two steps; first, the determination of the control variables, and second, the determination of the power output of the CHP system, which is done on the basis of the objective function as well as the problem constraints for the control variables. In addition, in the two above-mentioned steps, other parameters are also specified, which include installation location and the maximum capacity of CHP. The first two factors are specified in the first step, while the maximum capacity is defined in the second step. The problem is solved in the following process:

Step 1-1) Generating randomly the initial population

Step 2-1) Creating the required scenarios on the basis of the number of CHP systems, i.e., 2^n-1 (n stands for the number of CHP systems) in order to compute the maximum capacity of CHP. For instance, in case four CHP systems exist, there will be fifteen scenarios; when they are divided into 3 cases, the capacity of the CHP systems will be changed in a way to cope with the constraints and microgrid loading. The three cases are presented below:

Case 1) Capacity of the three CHP systems is variable and that of the fourth one is constant.

Case 2) Capacity of the two CHP systems is variable and that of the other two is constant.

Case 3) Capacity of the one CHP system is variable and that of the other three is constant.

Case 4) Capacity of all four CHP systems is variable.

Step 2-2: Determining the CHP maximum capacity for each scenario in the former step as follows:

- **A)** If the voltage deviation of MG is exceeded, the capacity of the CHP systems is increased in a way to keep the voltage deviation in the allowed range.
- **B)** In case the standard deviation of the MG voltage is smaller than the optimal value and the lines loading is more than the value required, then the CHP systems capacity is decreased in order to make sure that the loading of the lines is kept in the allowed range.
- **C)** The steps noted above are applied to all stages; then, the results obtained from all the scenarios are saved on the basis of the defined objective function.

Step 2-3) Extracting a scenario (from among various available scenarios) with minimum losses related to the control variables mentioned in step 1.

Step 1-2) The primary particle population is sorted on the basis of the objective function.

Step 1-3) The gbest and pbest positions are extracted from the sorted population.

Step 1-4) Updating of the particles' acceleration is done.

Step 1-5) The positions of the particles are updated at this stage.

Step 1-6) The initial population of particles is sorted on the basis of the objective function that has been assessed before.

Step 1-7) The gbest and pbest positions are extracted from the updated population.

Step 1-8) If the convergence conditions are satisfied, the operation ends; otherwise, go to Step 2-1. The convergence conditions are considered to achieve the best value of the objective function as well as to ensure maximum repeatability of the algorithm.

The graphical representation of the PSO technique of the proposed method is illustrated in Fig. 2.

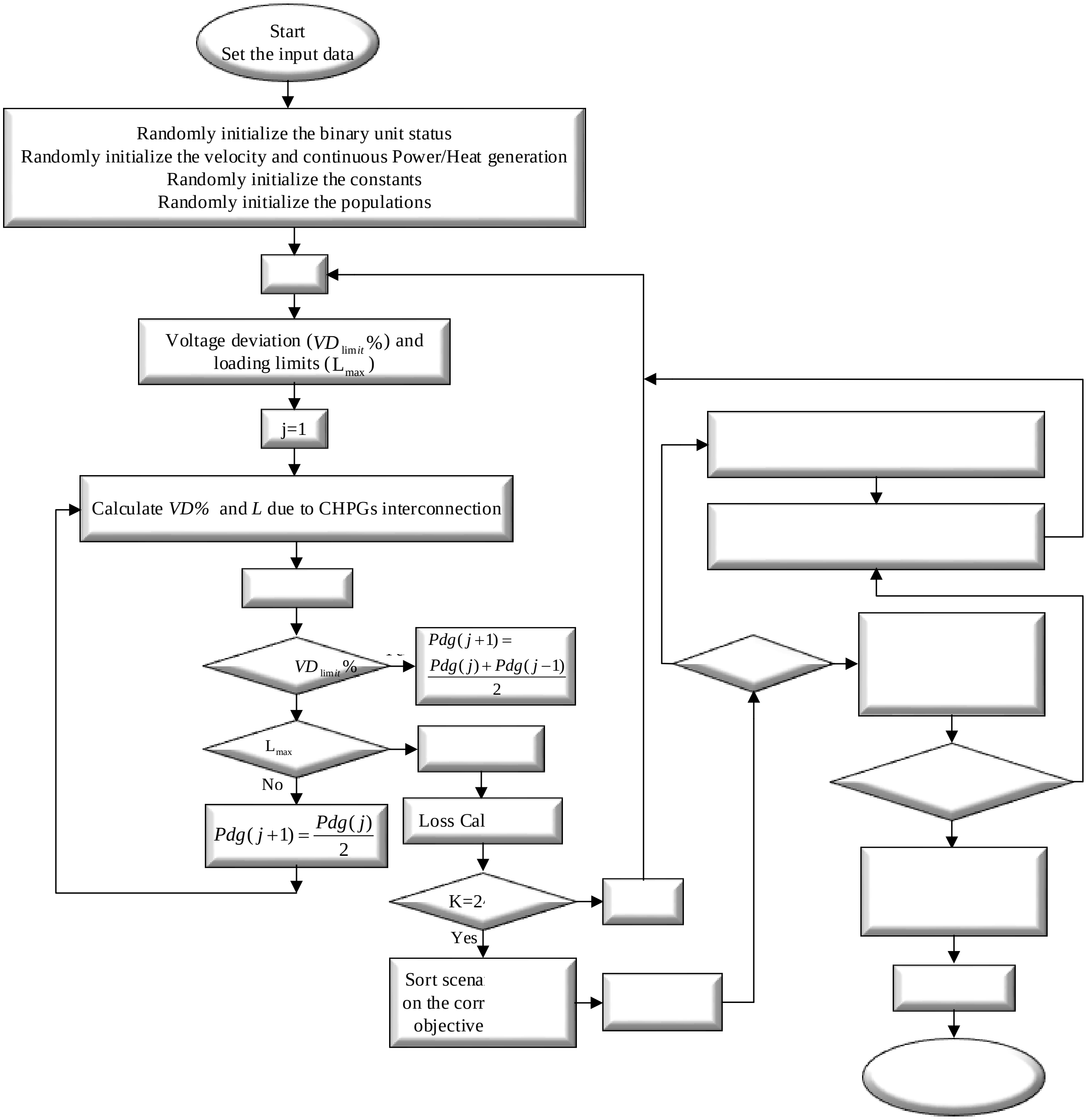

Fig. 2. Outline of PSO technique for solving CHP problem.

5. Simulation results and discussion

5.1. 84-bus meshed microgrid

The MG that was analysed was an 84-bus IEEE grid; a single-line diagram of this grid is illustrated in Fig. 3, where it is connected to the MG bus. The MG is divided into four zones, and four CHP systems are located in these four zones. Therefore, a CHP system is taken into consideration in the case of each zone. The 84-bus grid of the MG has active and reactive loads of 28300 and 20750 kW, respectively. This MG's loss is totally 7585.7 kW according to loading condition in Fig. 4

during peak 24 hours, and its minimum voltage takes place at bus 12 (i.e., 0.9286). Information regarding this MG was obtained from a previous study [15]. Here, each CHP's maximum capacity is assumed to be 3 MW.

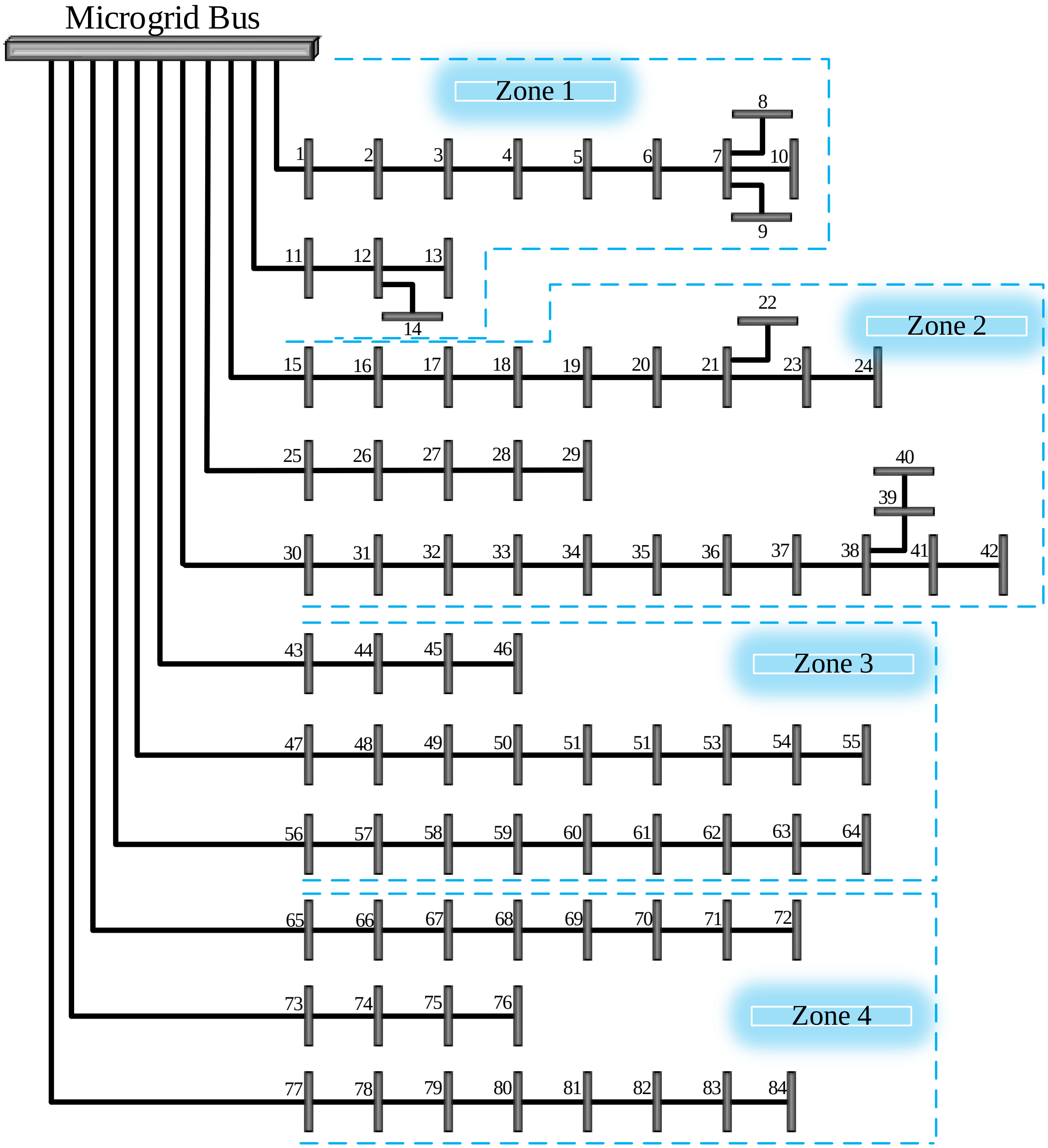

Fig. 3. 84-bus meshed microgrid (MG).

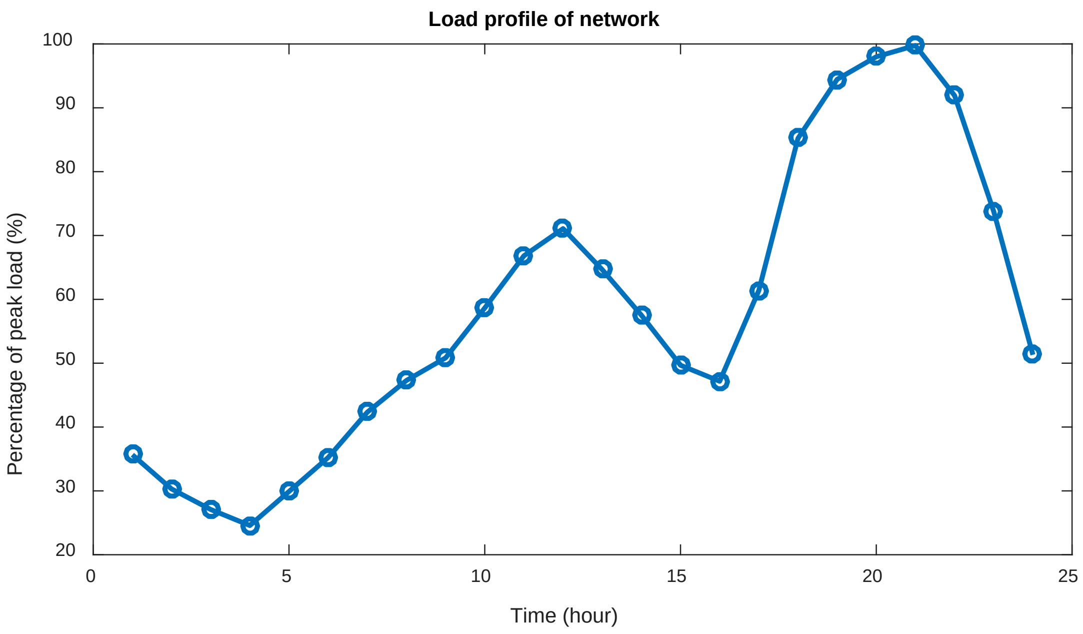

Fig. 4. Loading profile of understudy network

The PSO algorithm is applied to solve the allocation problem. The number of populations and maximum iterations of the algorithm are considered based on the trial and error method and the user experience in achieving the optimal solution and converging the algorithms. In the current research, the population of the algorithm was considered to be 50, and the maximum number of iterations of the algorithm was 100. Results of 84 bus distribution network considering CHP number increasing is presented in Table 1.

According to the obtained results in Table 1, it can be seen that optimum CHP allocation reduces power losses, reduces voltage deviations of the network buses, as well as improves the reliability or decreases the ENS. The results showed that increasing the number of CHPs further improved network characteristics. Therefore, the optimization program improves the performance of the network by determining the optimal installation location and also considering the variable loading of the network by generating the optimal variable capacity of CHPs. The results show that with optimal allocation of 4 CHPs, the network losses decreased from 7585.7 kW to 4250.5 kW during 24 hours, the ENS decreased from 17.47 MWh to 3.44 MWh and in addition the minimum grid voltage from 0.9286 p.u increased by 0.9601 p.u. Figs. 5-8, show the CHP power variations curves for different cases based on Table 1.

Table 1. Results of 84 bus microgrid considering CHP number increasing

Item/Values	Base Net	1 CHP	2 CHP	3 CHP	4 CHP
Size (kW)/Location (bus)	--	2472/9	2909/83 2623/8	2434/83 2218/56 3000/8	1887/84 2695/9 2146/56 2101/32
Power Losses (kW)	7585.7	6039.8	5180.1	4762.9	4250.5
ENS (MWh/yr)	17.47	9.09	7.46	5.22	3.44
Minimum Voltage (p.u)	0.9286	0.9479	0.9489	0.9601	0.9601
Maximum Voltage (p.u)	0.9501	0.9610	0.9612	0.9723	0.9723

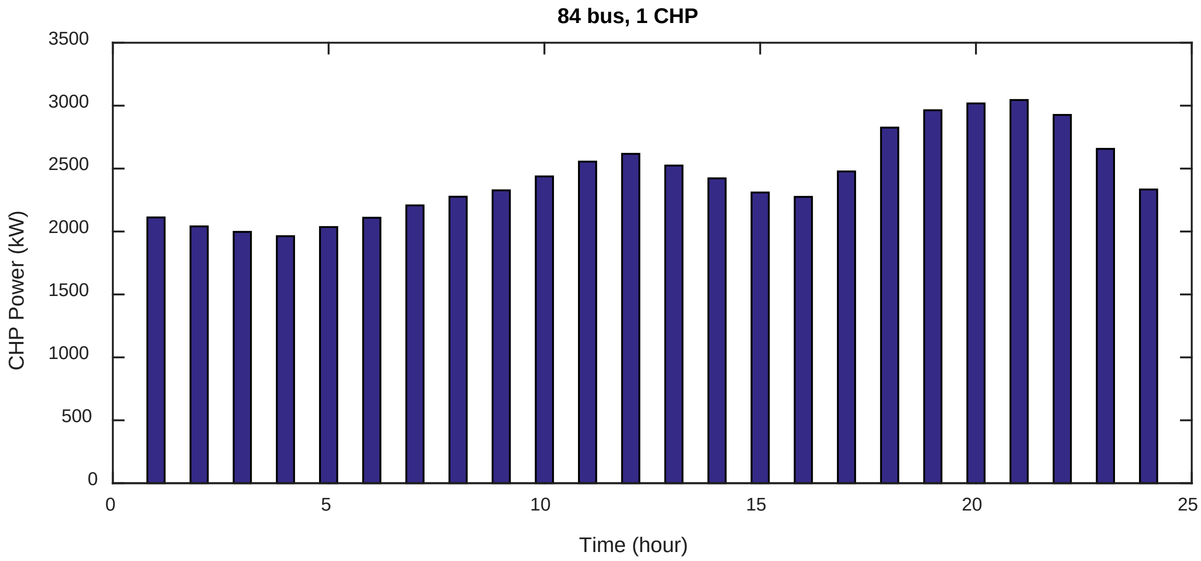

Fig. 5. Power variation of 1 CHP in 84 bus microgrid

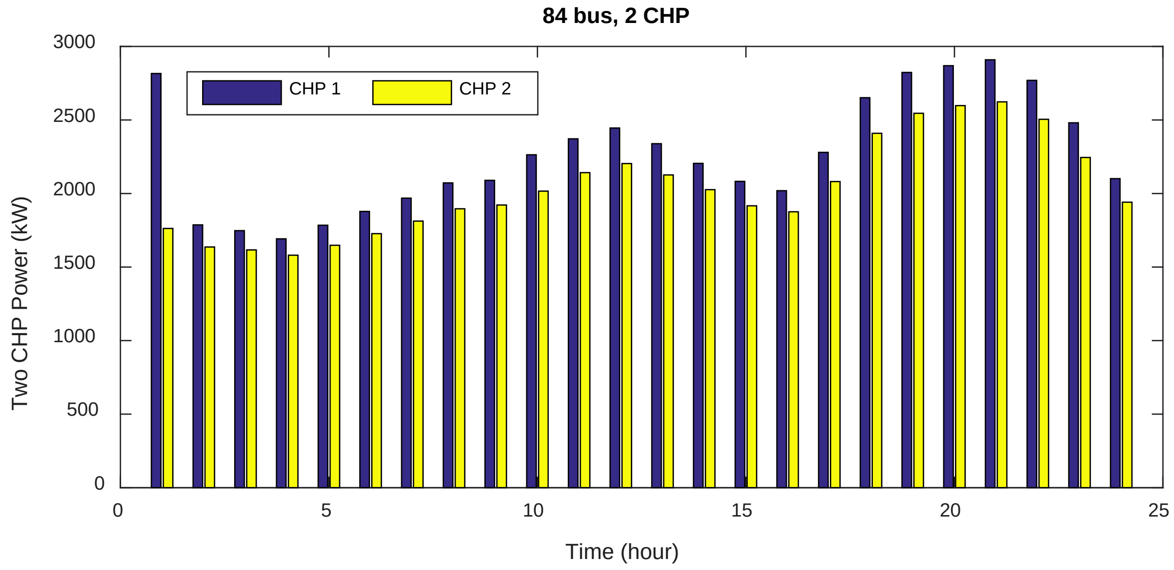

Fig. 6. Power variation of 2 CHP in 84 bus microgrid

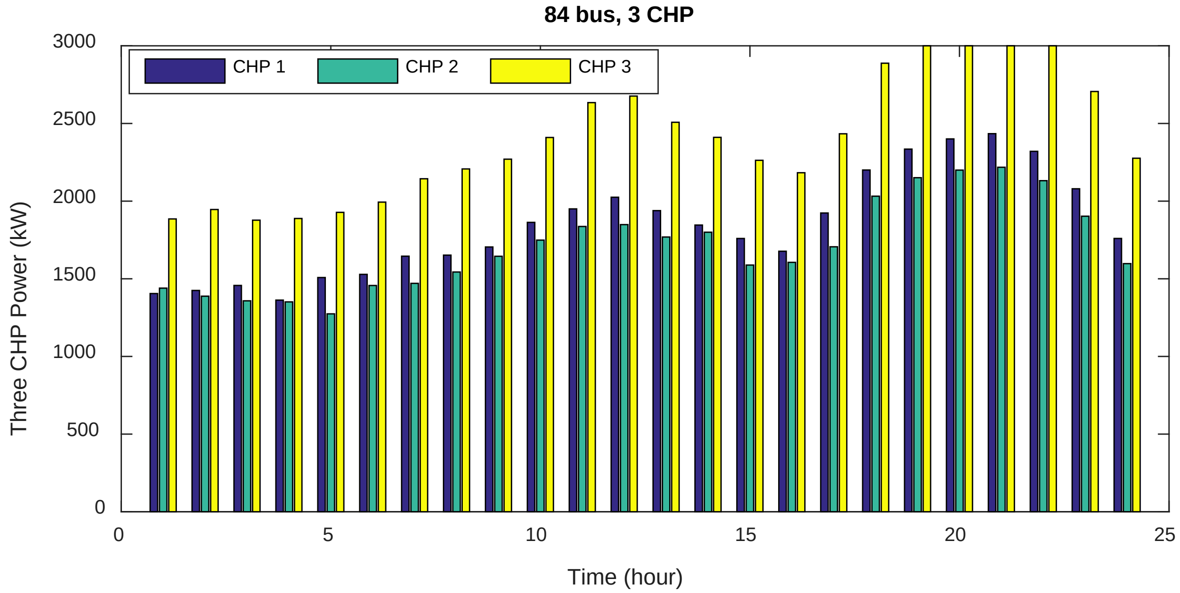

Fig. 7. Power variation of 3 CHP in 84 bus microgrid

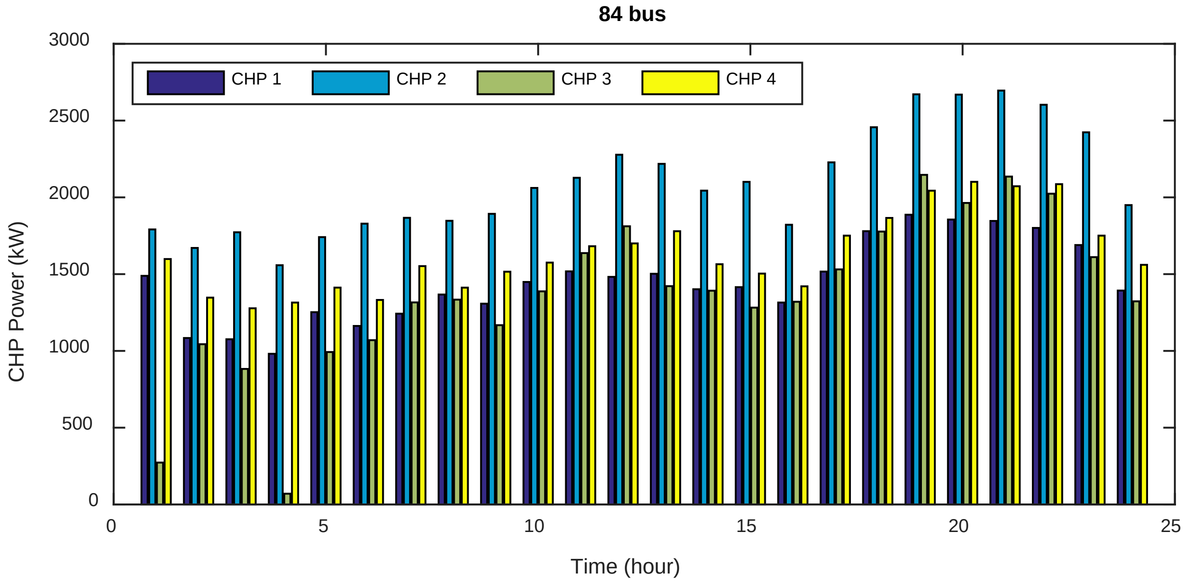

Fig. 8. Power variation of 4 CHP in 84 bus microgrid

In Figs. 9-11, the power loss curve, the minimum voltage of the grid and the ENS variations for the 84-bus grid are plotted for 24 hours a day considering 4 CHP allocation conditions. The results showed that optimization of the location and capacity of the CHP units using PSO decreased network losses and voltage deviations and also improved the reliability of the network customers by significantly ENS reduction.

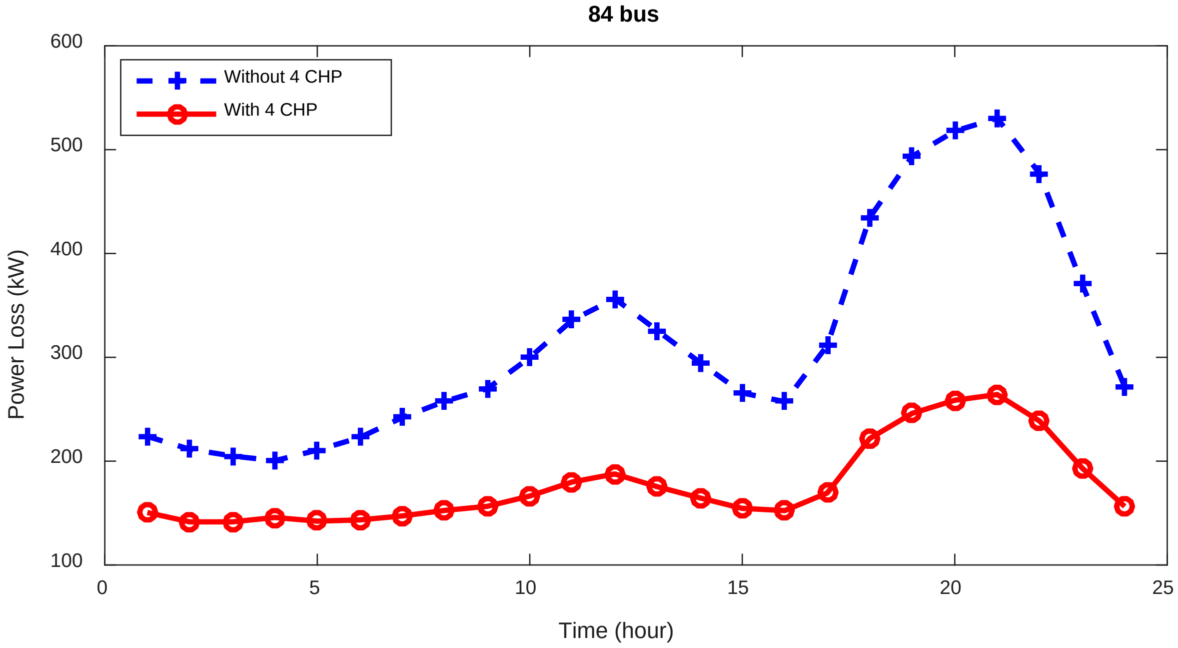

Fig. 9. Power loss variation of 84 bus microgrid with and without 4 CHP during 24 hours

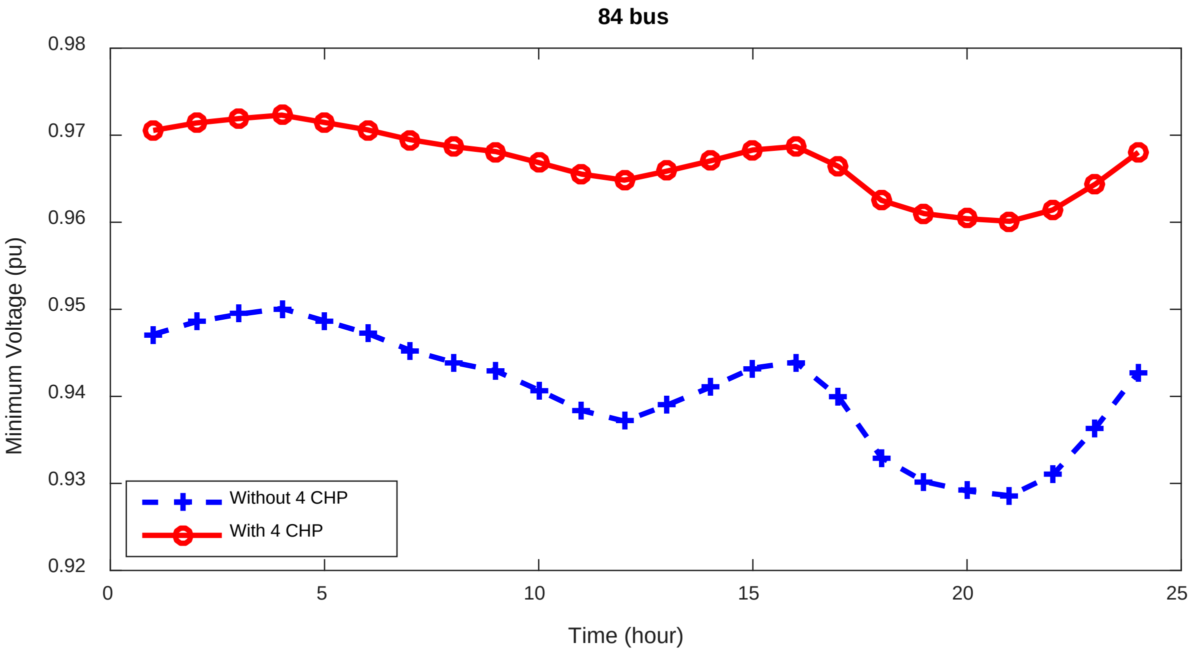

Fig. 10. Minimum voltage variation of 84 bus microgrid with and without 4 CHP during 24 hours

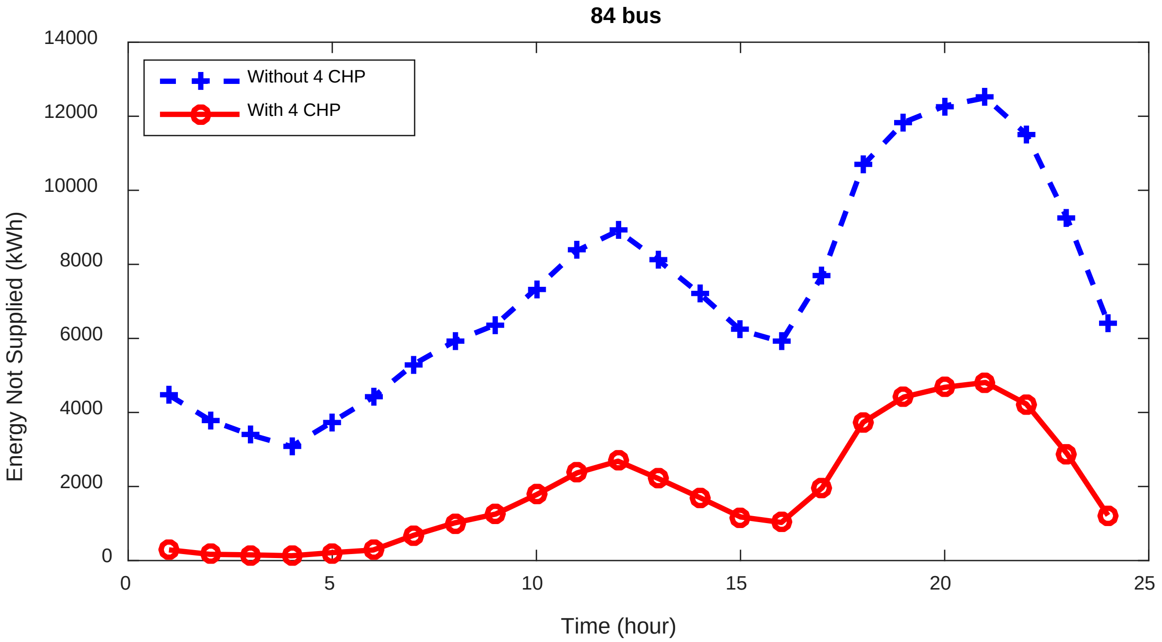

Fig. 11. ENS variation of 84 bus microgrid with and without 4 CHP during 24 hours

In Table 2, the simulation results of the 4 cases considered in section 4.2 for the 84-bus network are presented. In case 4, the capacity of all CHPs is considered variable but in other cases, the capacity of at least one CHP is considered constant. The results showed that when the capacity of all CHP units is varied and optimized by the optimization program, the network losses, network voltage deviations and ENS decrease further. The PSO method determines the optimum capacity with respect to network loading and network data to obtain the best positive effect on network characteristics also considering network utilization constraints. The lowest power loss is in case 4 and the highest is related to case 3. The highest reliability improvement is for Case 4 and the least for Case 3.

Table 2. Results of 84 bus distribution microgrid considering different cases

Item/Values	Base Net	Case 1	Case 2	Case 3	Case 4
Size (kW)/Location (bus)	--	3000/20 2991/2 2895/81 2055/56	3000/84 3000/9 2146/56 2101/32	3000/84 3000/9 3000/20 2101/56	1887/84 2695/9 2146/56 2101/32
Power Losses (kW)	7585.7	4687.6	5014.6	5350.5	4250.5
ENS (MWh/yr)	17.47	5.62	5.85	5.98	3.44
Minimum Voltage (p.u)	0.9286	0.9601	0.9600	0.9600	0.9601
Maximum Voltage (p.u)	0.9501	0.9723	0.9719	0.9719	0.9723

The performance of the PSO in optimal CHP allocation is evaluated with a powerful algorithm like a genetic algorithm (GA) considering constraint and based on multi-objective optimization. It should be noted that each optimization program is executed 20 times and the best result is saved. The convergence of the different algorithm in problem solution is presented in Fig. 12. As clear in Fig. 12, the PSO method is achieved to better objective function than the GA. Also, numerical results are presented in Table 3. According to the obtained results, the superiority of the PSO is proved with achieving less power loss and better voltage condition and also reliability in comparison with the GA. Numerical results of the proposed method compared with GA for 84 bus network (Case 4) is presented in Table 3. As can be seen in Table 3, the PSO method yields better results in terms of loss and reliability than the GA method.

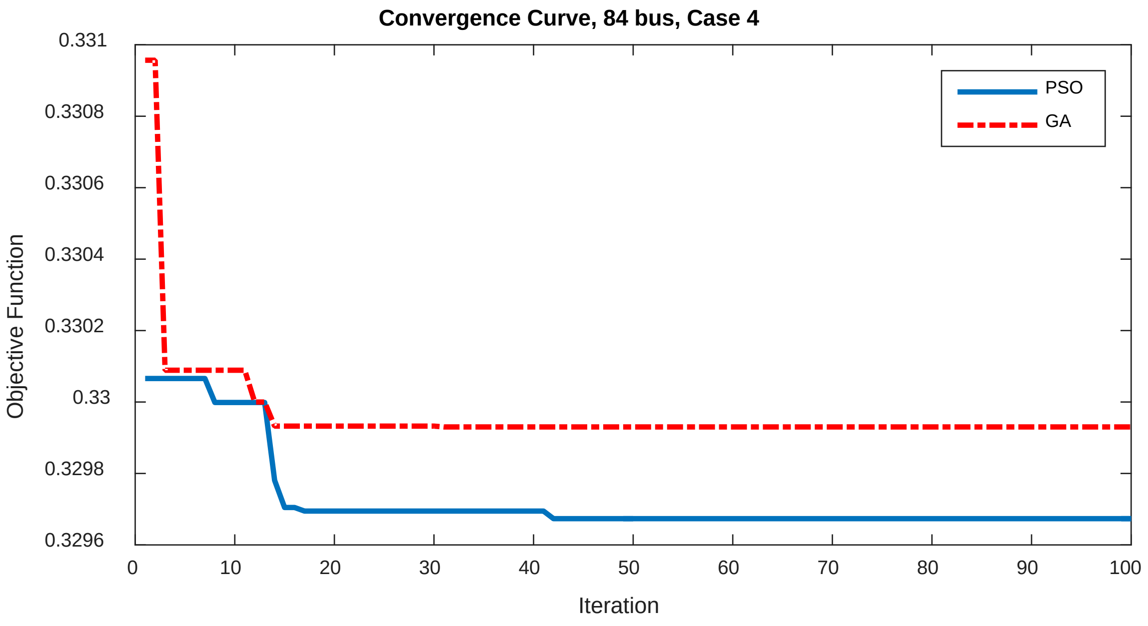

Fig. 12. Convergence curve of PSO and GA in CHPs allocation (Case 4) for 84 bus microgrid

Table 3. Performance evaluation of proposed method compared with GA for 84 bus microgrid (Case 4)

Item/Algorithms	PSO	GA
Size (kW)/Location (bus)	1887/84 2695/9 2146/56 2101/32	3000/2 1868/85 2154/74 2984/7
Power Losses (kW)	4250.5	4383.7
ENS (MWh/yr)	3.44	3.60
Minimum Voltage (p.u)	0.9601	0.9601
Maximum Voltage (p.u)	0.9723	0.9723

5.2. 32-bus meshed microgrid

The second MG considered was a 32-bus grid and is illustrated in Fig. 13. The single-line diagram of this grid is displayed as two distinct zones. The information on this MG was obtained from [15]. In this case, the maximum capacity of each CHP system was considered to be 1 MW. The 32-bus grid under normal condition demonstrated an active loss of 2778.5 Kw during 24 hours.

Distribution systems operate at lower voltages which means the lines carry more current. This calls for a thicker conductor to carry the current without melting. The high R/X ratio of distribution lines isn't the reason those conductors are chosen. For this purpose, there isn't an inherent advantage because of the high R/X ratio. Rather the larger conductors can carry more current which is necessary for the distribution system. Therefore these conductors have a higher resistance than conductors used for transmission line and thus higher losses.

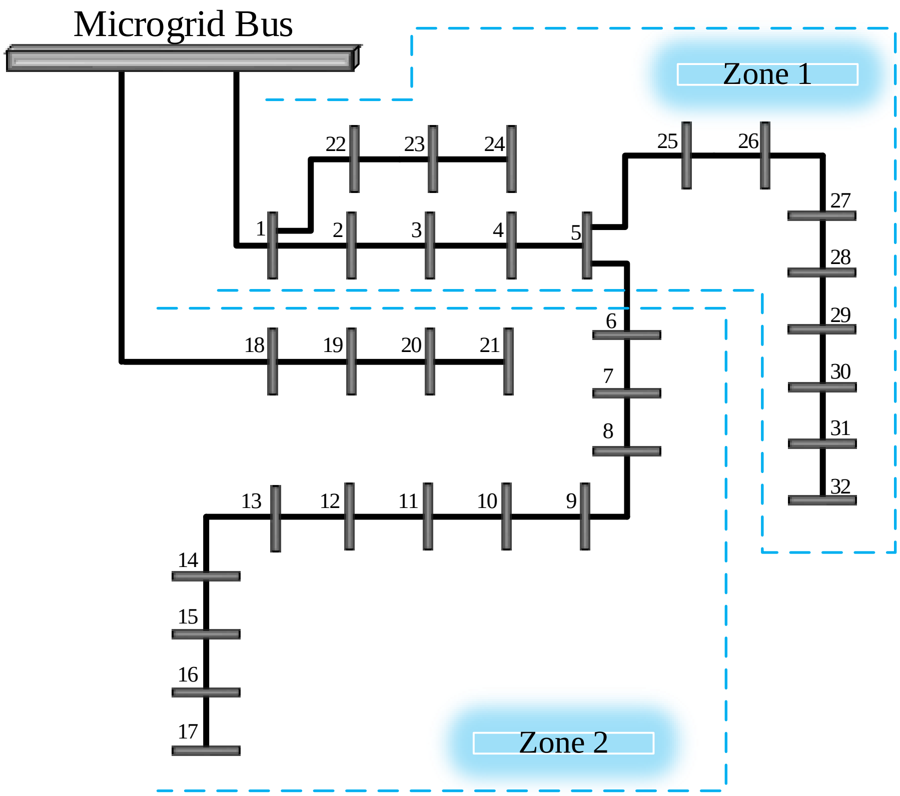

Fig. 13. 32-bus meshed MG.

In this section, at first, the optimal allocation of 1 and 2 CHP units in the 32-bus network is performed using the PSO method. In this simulation, the population number and maximum iteration of PSO algorithm are considered 30 and 100, respectively. The numerical results of the simulation are presented in Table 4, which shows that the optimal CHP allocation reduces power losses, reduces the voltage deviations of the network buses and also reduces the ENS. Increasing the number of CHPs has also led to a further reduction in losses, voltage deviations and ENS. The results show that with the optimal allocation of 2 CHP units, the grid losses decreased from 2778.5 kW to 777.37 kW during 24 hours, the ENS decreased from 11.98 MW to 1.96 MW, and in addition the minimum grid voltage from 0.9130 p.u increased to 0.9696 p.u. Figs. 14-17 show the power curves of CHP units as well as the power loss, minimum voltage and ENS curves for 24 hours.

Table 4. Results of 32 bus microgrid considering CHP number increasing

Item/Values	Base Net	1 CHP	2 CHP
Size (kW)/Location (bus)	--	1000/28	959.7/12 966.5/28
Power Losses (kW)	2778.5	1268.7	777.37
ENS (MWh/yr)	11.98	5.09	1.96
Minimum Voltage (p.u)	0.9130	0.9348	0.9696
Maximum Voltage (p.u)	0.9582	0.9791	0.9897

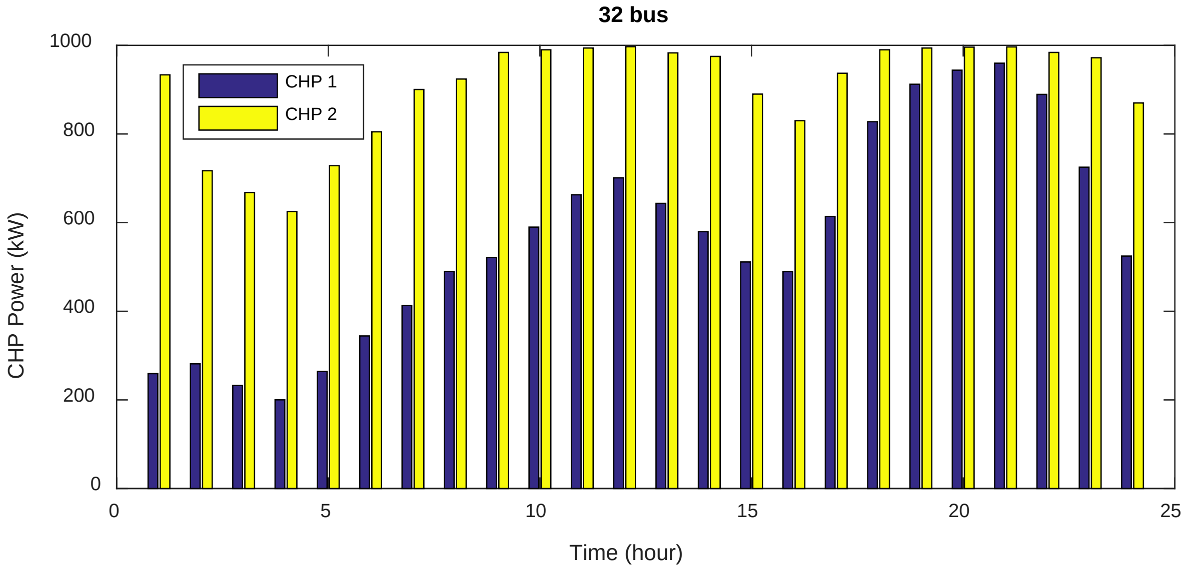

Fig. 14. Power variation of 2 CHP in 32 bus microgrid

In Figs. 15-17, the power loss variation curve, network minimum voltage and ENS variation are plotted for a 32-bus network for allocation of 2 CHPs during 24 hours. By optimizing the location and capacity of the CHP units by PSO, the network losses and voltage deviations are reduced and the network reliability is improved significantly.

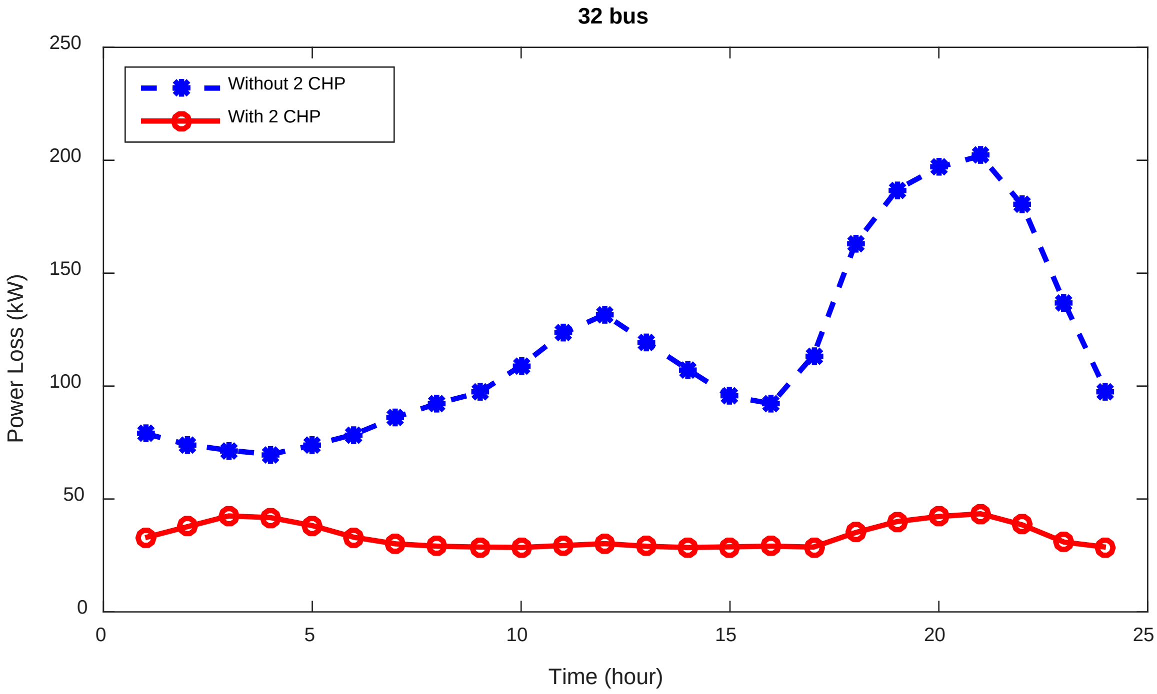

Fig. 15. Power loss variation of 32 bus microgrid with and without 2 CHP during 24 hours

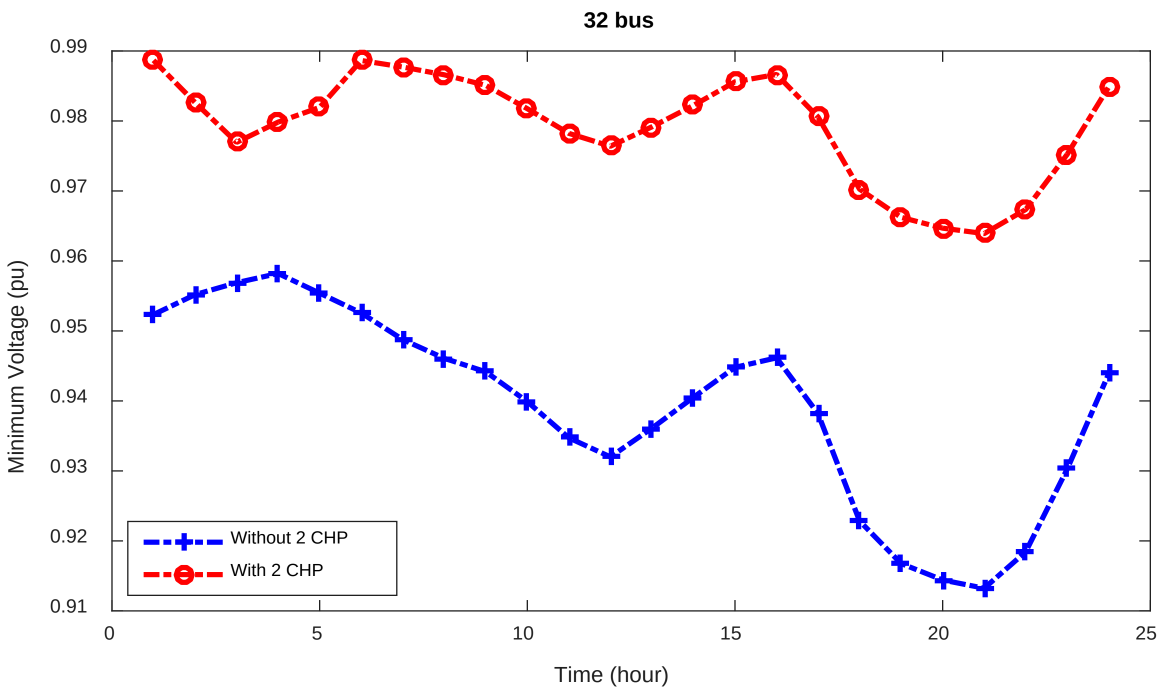

Fig. 16. Minimum voltage variation of 32 bus microgrid with and without 2 CHP during 24 hours

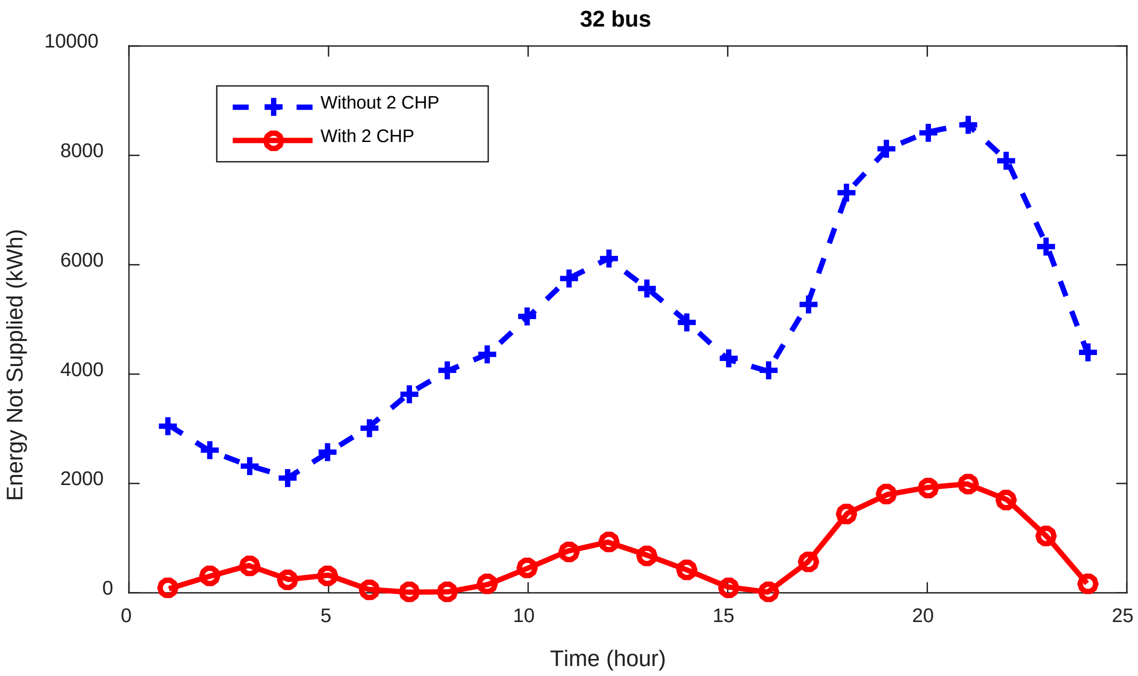

Fig. 17. ENS variation of 32 bus microgrid with and without 2 CHP during 24 hours

In Table 5, the simulation results of the two cases considered in section 4.2 for the 32-bus network are presented. In case 1, the capacity of a CHP unit is assumed to be constant (1 MWh). But in case 2, the capacity of both CHPs is considered variable. The results showed that in terms of the variable capacity of both CHP and determination of optimum capacity by optimization algorithm based on grid parameters and also load and operation constraints the network losses, network voltage deviations as well as ENS are reduced. The lowest power loss is in Case 2 and the highest in Case 1. The highest reliability improvement is related to Case 2 and the least for Case 1.

Table 5. Results of 84 bus distribution microgrid considering CHP number increasing

Item/Values	Base Net	Case 1	Case 2
Size (kW)/Location (bus)	--	1000/9 938/30	959.7/12 966.5/28
Power Losses (kW)	2778.5	805.19	777.37
ENS (MWh/yr)	11.98	2.07	1.96
Minimum Voltage (p.u)	0.9130	0.9669	0.9696
Maximum Voltage (p.u)	0.9582	0.9887	0.9897

The capability of the PSO in optimal CHP allocation is evaluated with GA powerful algorithm considering constraint and based on multi-objective optimization for 32 bus grid. The convergence curve of PSO and GA is presented in Fig. 18. As clear in Fig. 18, the PSO method is obtained better objective function than the other algorithms. Numerical results are presented in Table 6. According to the obtained results, the superiority of the PSO is confirmed with achieving less power loss and better reliability in comparison with GA.

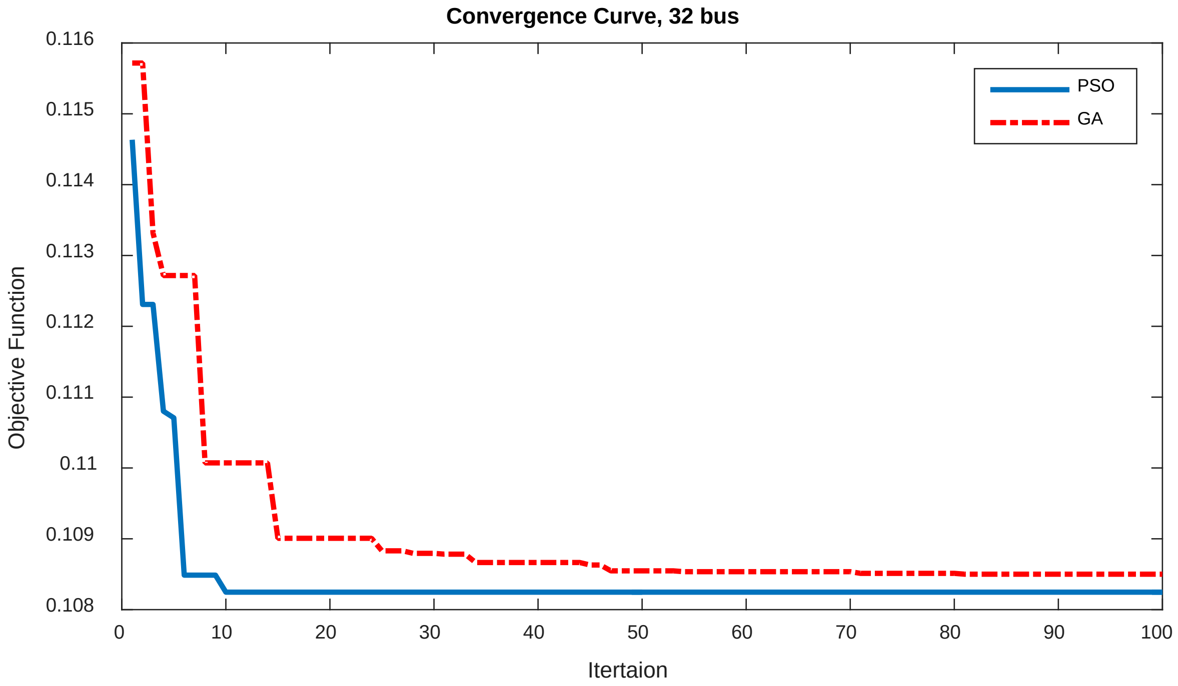

Fig. 18. Convergence curve of PSO and GA in CHPs allocation (Case 2) for 32 bus network

Table 6. Performance evaluation of the proposed method compared with GA for 32 bus microgrid (Case 2)

Item/Algorithms	PSO	GA
Size (kW)/Location (bus)	959.7/12 966.5/28	949.3/9 985.7/25
Power Losses (kW)	777.37	784.25
ENS (MWh/yr)	1.96	2.06
Minimum Voltage (p.u)	0.9696	0.9696
Maximum Voltage (p.u)	0.9897	0.9897

6. Conclusion

This paper presented a method that uses particle swarm optimization to select the optimal allocation for combined heat and power systems considering maximum allowable capacity with power loss reduction, voltage profile and reliability improvement of microgrids considering network loading condition. This problem is presented as a multi-objective problem based on the weight factors method. The decision variables were the location and capacity of the combined heat and power systems that were determined optimally. The proposed method was applied to 84- and 32-bus standard microgrids. This approach is applied two-stage particle swarm optimization algorithm for the purpose of facilitating the allocation process of combined heat and power systems regarding their maximum capacity. The results confirmed that the proposed method was able to determine the optimal location and size for combined heat and power systems with improving the customer's reliability and voltage profile and also reducing the power losses in an effective and rapid approach. The results showed that considering variable combined heat and power capacity allows the optimization algorithm to select the appropriate combined heat and power capacity for installation so that the operating constraints are within the permissible range and obtain the best microgrid performance. Furthermore, the results cleared that when constraints were taken into account, the minimum possible losses resulted in the microgrid. Moreover, the loss, minimum voltage and energy not supplied are decreased by 43.9%, 3,4% and 80.31% for 84 bus network and 72%, 6.2% and 83.6% for 32 bus network, respectively, using particle swarm optimization by optimal combined heat and power systems allocation in comparison with a base network.

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