The application of Imperialist Competitive Algorithm to the combined heat and power economic dispatch problem

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Manuscript received 20 April, 2018; September 20 July, 2018, accepted 2 October,2018. Paper no. JEMT-1804-1083.

As the penetration of multicarrier energy systems in power grid increases, the economical optimization analysis are becoming of increasing importance more and more. One of the most challenging issues in this context is optimizing the sophisticated combined carrier systems in power system operation field, especially solving the combined heat and power economic dispatch (CHPED) problems. This paper presents a solution for the sophisticated and non-convex CHPED problems applying the imperialist competitive algorithm (ICA). The idea of the introduced algorithm is derived from the social and political development of human societies. Different study cases by taking the effects of valve-point loading effect (VPLE) and transmission ohmic losses have been simulated to confirm the efficiency of the suggested algorithm. The obtained results from the ICA-based CHPED problem are compared with those obtained by various algorithms to prove the performance of the proposed algorithm in searching the optimal solution. As the results confirm, the ICA has superiority on CPSO, TVAC-PSO, RCGA, RCO, BCO, EP, DE, EMA, CSO, RCGA-IMM and GSA, which were previously proposed in this domain for solving the described problem.

keywords: *ICA, combined heat and power economic dispatch, heuristic algorithm, electrical losses, value-point effect.*

http://dx.doi.org/10.22109/jemt.2018.141453.1111

1. INTRODUCTION

This paper introduces the application of ICA to CHPED problem, as one of the most important problems in the planning and control issues of integrated power and heat systems. For this purpose, the definition of CHPED problem and some relevant tasks are firstly described. The previous related works are then reviewed and finally, the main contributions of this work are summarized.

A. CHPED Problem concept

In recent years, the research focus on power systems has been changed, drastically. Initially, the main issues were related to the voltage improvement and the power network expansion planning. Although in many developing countries, these domains are still of interest, nonetheless, in industrialized countries, the most important areas of interests are tackling with increasing the security or reliability of the extended power systems. The power system security is influenced by the greater dependence to the power grid, and access to more generation is related to the nature of the system and deals with macroeconomic issues.

Recently, several issues of world-wide energy infrastructures were evolved, and it is questioned whether these emerging systems can meet our future increasing needs for different types of energy? Along with composite energy transfer systems, many of the equipment will be close to their lifetime. In addition, challenges such as supplying the continuous growth of energy demand, dependence on fossil fuels, renewal of power system equipment's, and using of clean and sustainable energy resources raise the need for new energy systems along with some basic changes in existing systems. As these changes are applied in power systems, revising the traditional tools applied to power system operation and planning issues are needed.

One of the most challenging topics in today's power system is the optimal operation of power networks. This problem, which is nominated as economic load dispatch (ELD) searches the optimal power of generation unit outputs, to supply the demanded load, satisfy the different constraints, at the lowest cost.

Despite the development of renewable energies, a large amount of energy is still supplied by fossil fuels. The average efficiency of fossil-fueled power plants in the America is 33 %. So increasing fuel efficiency is essential. One of the best solutions is the combination of heat and power.

CHP is technology which generates power and captures the heat. Generally the heat may be wasted in order to providing some kinds of thermal energy. The steam or hot water are good examples in this regard, which can be applied to space heating appliances, cooling, and some industrial applications. CHP which is abundantly used as a solution to increase the fuel efficiency, has several advantages in compare to conventional electricity and thermal energy production. This system retrieves wasted heat and applying it will be resulted in increasing the efficiencies to upper than 70% [1] for power generation and useful heat. There are some reports in this regard which insist on achieving the efficiencies up to 90% [2, 3]. More efficiency means burning less fuel to produce each unit of energy. A CHP unit can reduce about 13-18% the environment emissions of the generation [3]. The power dispatch is not a new concept, and CHPED was solved in the third decade of the 19th century. However, it still has some drawbacks, which means it needs to be improved and searched to getting some optimal solutions. The purpose of CHPED problem is minimizing the fuel cost in such way that all the equality and non-equality constraints are met for different units. The complex and sophisticated structure of the CHPED problem is such that it cannot be easily solved applying some classical methods such as lambda-iteration, interior point, and quasi-Newton methods. The performance of any suggested algorithm in this field should be compared with the other well-known algorithms in terms of economic benefits. This comparison results in verifying the algorithms performance in reaching the operating point at a lower cost.

B. Literature review and challenges of CHPED problem

The literature review shows that there are mainly three factors in regard to the CHPED optimization problem, which make it very nonlinear, non-smooth, and non-convex. These factors are described hereafter:

1. VPLE [4] will cause ripples to the fuel-cost curve. The fuel cost function will be smooth and define as a quadratic curve in the absence of VPLE. It affects the input-output characteristics of generating power units. It also causes the non-linear and non-smooth of the generation unit output.

2. In CHP units, the power generation capacity as well as the heat generation quantity depends on each other [1]. This interdependence of generated power and heat in CHP units will restrict the operation of CHP units. This subject is at the heart of the most important research in the CHP operation field.

3. The power system losses caused by the realistic AC nature of electrical networks must be supplied through the generation units. The electrical losses as a main factor should be considered in power balance equation. Therefore, the optimization methods needed to search for the CHPED problem solutions considering the ability to find the global minima. Otherwise they will be trapped in some local optimum points. The literature proposed different algorithms and methods applied to this optimization problem.

VPLEs makes it possible to create more than one local minima. The method based on gradient generally get trapped in the quasi optimal or local extremism points. The two-layer algorithm based Lagrangian relaxation used in [5] and also, some nonlinear-based approaches such as quadratic and dual programming [6] cannot to be used for these complex problems. For this reason, the meta-heuristic algorithms have been addressed to implement to the CHPED problem. References [2], and [7] employed harmony search algorithm (HSA) to the economic CHP problem with constraints and regardless of the VPLE. An extended version of particle swarm optimization (PSO) method known as improved PSO (IPSO) has been used in ref. [8] for solving the CHPED considering multiple objectives in a multi-objective optimization manner. Also, to solve the multi-objective problem concluding CHPED and emission problems, ref. [9] introduced a two-stage approach by combining multi-objective optimization with integrated decision making. Also, the mentioned multi-objective problem is solved by considering the fuel cell (FC), boiler, storage system, and heat buffer tank by Nazari-Heris et al. in ref. [10].

Ref. [11] suggested a hybrid algorithm known as IGA_MU to deal with the mentioned problem. Also, the authors in ref. [12] suggested the CSO algorithm to tackle with the CHPED in presence of a large amounts of local minima points. Cuckoo search method [13] introduced by Mohamed Arezki Mellal for solving the CHPED problem. In this regard, an algorithm providing a better solution based on PSO algorithm, known as SPSO in reported in [14]. Hosseini et al. in [15] proposed a mesh-based algorithm which directly search the best points in order to find the CHPED optimal point. Rashedi et al in [16] introduced GSA algorithm and Derafshi and et al successfully applied it to the CHPED problem [17]. In this field, the DE in [1], GSA in [17], TVAC-PSO in [18], and BCO in [19] are proposed to solve the mentioned problem concluding the VPLE incorporating with electrical transmission ohmic losses. In order to solve the CHPED problem by considering prohibited zones of thermal power plants, the transmission ohmic losses as well as the VPLE, Murugan et al. in [20] and pattanaik et al in [21] presented hybridizing BA and ABC with Chaotic based Self-Adaptive (CSA) and modified teaching-learning-based optimization, respectively. Furthermore, in order to improve the optimization technique, reference [22] have proposed the embedding CSO and Powell's pattern search method.

Also reference [23] applied whale optimization algorithm (WOA) to this problem. The authors reported the simulation case study regarding to standard cases and proved the ability and performance of the presented method. Reference [24] applied a meta-heuristic algorithm known as an improved version of social cognitive optimization (SCO) algorithm with tent map known as TSCO to the mentioned problem. The text is enhanced by presenting 2 case study results. Also this problem is addressed in [25], in which the frog leaping algorithm (LFA) is used to solving that problem. The case study simulation results on standard power systems are detailed by the authors.

Furthermore, Ghorbani in [26], introduced the application of exchange market algorithm (EMA) to CHPED problem. He also detailed the results regarding applying this algorithm to five well-known case studies, and compared the obtained results with other evolutionary algorithms. The crisscross optimization (CSO) algorithm was implemented to CHPED by Meng et al. in [27] considering two interacting operators, namely horizontal and vertical crossovers. They also applied the CSO on some standard CHPED problems and demonstrated the proposed algorithm features. The authors in [28] have proposed a real coded genetic algorithm with improved Mühlenbein mutation (RCGA-IMM) for solving CHPED problem. They implemented a Mühlenbein mutation on basic RCGA for speeding up the convergence and improving the optimization problem results. The detailed results obtained by the proposed algorithm on four standard case are reported and compared with the other algorithms in this area.

Contribution of this work

Recently, the authors of reference [29] suggested a social and political-based algorithm which models the man behavior known as ICA. This new algorithm has been employed to the several optimization problems such as Transmission Expansion Planning (TEP) matching [30], DG planning [31], optimal design of heat exchangers [32] and some electromagnetic problems [33]. All of the referred works claimed on good performance of the ICA. So, this proposed approach can be a good option for solving the complex problem of CHPED.

This paper deals with applying a new algorithm, ICA, to solve CHPED problem. The abovementioned algorithm has been adopted to various problems in different area of power system studies, such as planning and operation. As the authors know this algorithm has not been reported before to be applied to CHPED problem. So, the novelty of this paper mainly comes from its application to the CHPED for the first time. Furthermore, for checking the precision and performance of the suggested algorithm, different test systems have been selected.

Current manuscript is structured as follows: Section 2 explains the CHPED problem formulation. The ICA structure reviews in section 3. The details regarding the proposed ICA-based CHPED problem are addressed in later section. Section 5, compares the obtained simulation results on different standard cases by different algorithms to verify the effectiveness of the presented method. Eventually, the main conclusion of this work are presented in section 6.

2. MATHEMATICAL FORMULATION APPLIED TO CHPED PROBLEM

Basically, the CHPED problem mainly contains an objective cost function as well as some practical constraints. This problem is completely non-convex and non-linear in nature. So, the traditional and mathematical methods may not be resulted to finding optimal solutions. The general view of this problem can be easily found in the following:

A. Objective cost function

The main goal of a CHPED problem is minimizing the total fuel cost functions of power-only units (POUs), heat-only units (HOUs) and CHP units. The objective cost function is concluding three terms regarding the POUs, HOUs, and CHP units as follows:

$$\text{Min} \quad \sum_{i=1}^{N_P} C_i(P_i^p) + \sum_{j=1}^{N_c} C_j(P_j^c, H_j^c) + \sum_{k=1}^{N_h} C_k(H_k^h) \qquad \textbf{(1)}$$

where

$C_i(P_i^p) = \alpha_i(P_i^p)^2 + \beta_i P_i^p + \gamma_i$

$C_j(P_j^c, H_j^c) = a_j(P_j^c)^2 + b_j P_j^c + c_j + d_j(H_j^c)^2 + e_j H_j^c + f_j P_j^c H_j^c$

$C_k(H_k^h) = \alpha_k(H_k^h)^2 + \beta_k H_k^h + \gamma_k$

where $C_i(P_i^p)$ with$i = 1, 2, \ldots, N_p$ express the fuel cost of the *ith* POU in \$ for time horizon of 1 h, and α_i ,β_i and γ_i are the relevant cost parameters describing the cost function. Also, the fuel cost of a CHP unit j is presented by $C_j(P_j^c, H_j^c)$ with $j = 1, 2, \ldots, N_c$ in \$/h in which a_j, b_j, c_j, d_j, e_j, and f_j describing the relevant cost factors; $C_k(H_k^h)$ identifies the relevant cost function of *kth* HOU with $k = 1, 2, ..., N_h$ in \$/h and $\alpha_k, \beta_k \& \gamma_k$ describe the relevant cost parameters; the number of POUs, CHP units, and HOUs is demonstrated by N_p, N_c, and N_h; H_j^c, H_k^h, and P_i^p, P_j^c are the heat generation (in MWth) and unit power generation (in MW), respectively. Indexes h, k, c, j, and p, i, describing the relevant indexes for HOUs, CHP, and POUs.

Considering the impact of VPLE, add a sinusoidal form section to the objective cost function $C_i(P_i^p)$. Consequently, the objective cost function adding the VPLE will be as follows:

$$C_i(P_i^p) = \alpha_i(P_i^p)^2 + \beta_i P_i^p + \gamma_i + |\lambda_i \sin(\rho_i(P_i^{p,\min} - P_i^p))| \qquad \textbf{(2)}$$

In which the relevant cost coefficients of the VPLE impact are mentioned by λ_i and ρ_i.

B. Equality constraints

Equation (3) describes the power balance equation by considering the electrical ohmic losses in transmission system. Generally these losses are calculated applying B matrix method. This approach known as Kron's loss formula [34]. In current work we used the mentioned method in order to electrical loss calculations of power system. Furthermore, the total heat generated by the CHP units, and HOUs must be equal to the heat demand, which is stated in equation (4). As important note, the heat losses are not modeled in this study. It should be mentioned that the B Matrix coefficients for the standard cases are known and here we used the standard data in this regard.

$$\begin{aligned}&\sum_{i=1}^{N_p} P_i^p + \sum_{j=1}^{N_c} P_j^c = P_d + \\ &\left(\sum_{i=1}^{N_p} \sum_{l=1}^{N_p} P_i^p B_{il} P_l^p + \sum_{i=1}^{N_p} \sum_{j=1}^{N_c} P_i^p P_j^c + \sum_{j=1}^{N_c} \sum_{m=1}^{N_c} P_j^c B_{jm} P_m^c \right)\end{aligned} \qquad \textbf{(3)}$$

$$\sum_{j=1}^{N_c} H_j^c + \sum_{k=1}^{N_h} H_k^h = H_d \qquad \textbf{(4)}$$

In which H_d is the total demanded heat and P_d is the total demanded power of the combined power and heat network, respectively.

C. Inequality constraints

Because of some practical, operational, and economical issues, the generator capacities are restricted to some predefined power and heat limits. These constraints come from the different operation limitations of generation units. These limitations for POUs, CHP units, and HOUs are represented by the inequality constraints (5)-(8).

$$P_i^{p,\min} \leq P_i^p \leq P_i^{p,\max} \quad i = 1, 2, ..., N_p \qquad \textbf{(5)}$$

$$P_j^{c,\min}(H_j^c) \leq P_j^c \leq P_j^{c,\max}(H_j^c) \quad j = 1, 2, ..., N_c \qquad \textbf{(6)}$$

$$H_j^{c,\min}(P_j^c) \leq H_j^c \leq H_j^{c,\max}(P_j^c) \quad j = 1, 2, ..., N_c \qquad \textbf{(7)}$$

$$H_k^{h,\min} \leq H_k^h \leq H_k^{h,\max} \quad k = 1, 2, ..., N_h \qquad \textbf{(8)}$$

In which $P_i^{p,min}$, $H_k^{h,min}$ and $P_i^{p,max}$, $H_k^{h,max}$ represent the relevant maximum and minimum power and heat generations, respectively. We should keep in mind that in the CHP units, the power and the heat generation limits depends on the heat and power production, respectively. This means that the correspondent limits are affected by each other.

3. THE ICA STRUCTURE

ICA derived from social and political behavior of imperialism and colonies. Generally, the ICA starts in an assumed population which is known as the initial countries. This algorithm belongs to meta-heuristic category and has been proposed to solve the complicated and non-linear optimization problem. Such as the other meta-heuristic algorithms, ICA starts with a feasible solution and by evaluating in each iteration the solution will be close to optimal solution. The main steps of the proposed ICA are illustrated in Fig. 1. Some description regarding various steps of ICA are detailed in following sub-sections.

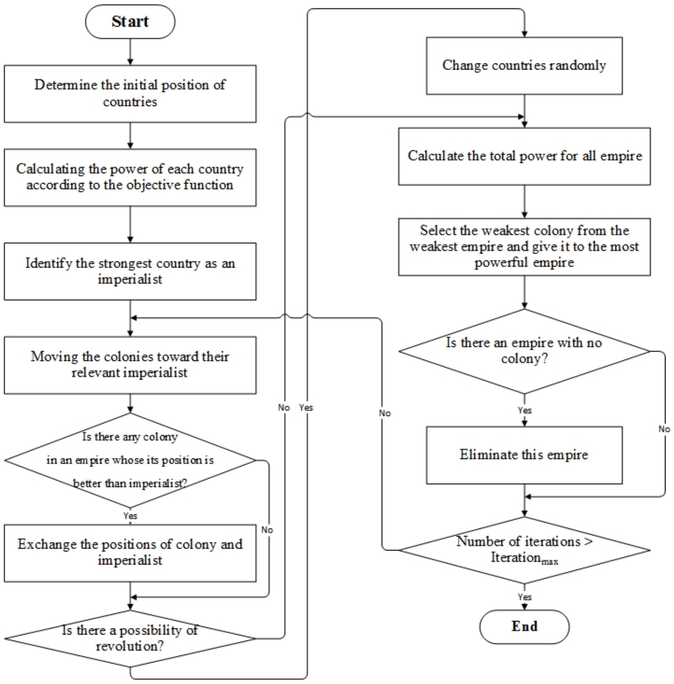


Fig. 1. Flowchart of ICA

A. Step 1: Generating Initial Empires

At first, countries are randomly assigned at a distance between their lower and upper bounds:

$$\mathrm{x}_{i,j}^{(0)} = x_{i,min} + rand.(x_{i,max} - x_{i,min}) \tag{9}$$

where $x_{i,j}^{(0)}$ specifies the starting value of the ith variable regarding to the jth country; $x_{i,\mathrm{min}}$ and $x_{i,\mathrm{max}}$ are the relevant mini-max permissive values for the ith variable. Also, the rand is a random number in the distance [0, 1] which is produced applying a random operator generator in MATLAB software [34]. The relevant power for each country is calculated according to the objective cost function (in the context of optimization is proportional to the inversion of its cost value, countries with lower costs are more powerful). N_{imp} which describes the numbers of the strongest countries are chosen as imperialists. The value of the N_{imp} can be selected from 1 to $N_{country}$. However, it is usually chosen to be $0.1 * N_{country}$. The relevant colonies regarding these imperialists are formed by the rest of countries. $N_{country}$ denotes the total number of countries. Selecting a large amount for $N_{country}$ makes the results more accurate but will be resulted in increasing the simulation time. There are different ways to allocate countries to an imperialist. In one way, after the determination of imperialists, countries can be divided equally between them. The jth imperialist together with their colonies form the jth Empire.

In this paper, all the countries are divided among the imperialists accidentally and a population of 100 countries including 10 empires has been used.

B. Step 2: movement of colonies

All the colonies move toward their imperialist. This displacement by adding a uniformly random distributed value in the distance 0 and $\beta \times d$, to the value of its variables is modeled as follows [29]:

$$\{x\}_{new} = \{x\}_{old} + U\,(0, \beta \times d) \tag{10}$$

$$\{x\}_{new} = \{x\}_{old} + \beta \times d \times \{rand\} \tag{11}$$

In which the β is a parameter which is greater than one, and d is the mathematical distance between imperialist and the colony. For increasing the searching space around the imperialist, a predefined random amount of deviation will be considered to be added to the movement direction. θ is a random uniform distribution number as follow:
$\theta = U\,(-\gamma, +\gamma)$
Where γ indicates the range of the deviation from the direction.

In most of the applications, some predefined values about 2 for β [19] and approximately 0.1 (Rad) for γ, are proposed in order to avoiding the trapping in local optimum and enhance the performance ability of the proposed algorithm.

In this paper, an initial country ($X0$) is taken to improve and accelerate ICA convergence. Any arbitrary value for variables of this country can be selected in order to finding an optimal point with good convergence. It should be mentioned that the country is selected as follow:

At first, the minimum value of variables is considered, then they are changed in such a way that the constraints of equality and inequality are met.

C. Step 3: The Imperialist and a Colony Exchanging Positions’

When colonies moves toward the imperialist, the colony and the imperialist will exchange their position, if a colony in its updated position is better than its relevant imperialist. This subject is evaluated applying the defined objective cost function. Accordingly, the rest colonies move to the updated position.

D. Step 4: Total Power Calculation for an Empire and Imperialist

In imperialistic competition, some of the colonies of the weakest empire are taken and all empires compete for possess these colonies. In each competition, the empires will have a likelihood for taking possession of the relevant colonies based on their total power. In this paper, this colony will be given to the most powerful empire.

The correspondent power to an empire is largely the result of imperialist power. It should be noted that the power of colonies also has little impact in this context. Thus, the total power of an empire, including the power of imperialist and its colonies, is as follows:

$$TC_j = f_{\cos t}^{(imp,j)} + \xi.mean(f_{\cos t}^{col,j}) \tag{12}$$

Where TC_j is specified as the total objective cost of the jth Empire and ξ is assumed to be a positive number less than 1. It should be mentioned that the power of each country is proportional to the inversion of its cost value. Whatever the value of ξ is larger, the effect of power the colonies will be higher. While choosing a small value for it causes the total power of an empire to be determined by just the imperialist. In most implementations, the value of 0.1 for ξ is a proper choice [29].

E. Step 5: Elimination of the Powerless Empires

During the imperialistic competition, powerless empires lose their colonies. When an empire loses all of its colonies, it is collapses and eliminates. Under these conditions, other empires compete for possess this empire as a colony. In this paper the empire will be given to the most powerful empire.

F. Step 6: Revolution

In this step, the probability of revolution is compared with a uniformly random value that distributed between 0 and 1. In this paper, the probability of revolution is 0.5. If there has been possibility of revolution, a random amount is added to one of the colony variables randomly. Otherwise, the colony will not change.

G. Step 7: Stopping criterion

The stopping criterion can be either reaching a single empire or reaching the maximum iteration. All of the above mentioned steps continue until the iteration number reaches to a predefined value of $Iteration_{max}$. As in important not, in this paper, the maximum number of iterations is supposed to be equal to 500.

4. APPLYING THE ICA TO THE PROBLEM

The main steps of solution the mentioned problem applying the ICA algorithm as a meta-heuristic algorithm are as follows:

The main steps of solution the mentioned problem applying the ICA algorithm as a meta-heuristic algorithm are as follows: Step 1. Introducing the relevant parameters of ICA such as $N_{country}$, N_{imp}, X0, β, ξ, γ, and $Iteration_{max}$.

Step 2. Determining the initial position of countries. In CHPED problem, the heat and power generation of different units concluding POUs, HOUs, and CHPs are the variables of each country which determine their position. They can be stochastically selected using the equations (13)–(16) [18] to satisfy all relevant inequality constraints:

$$\begin{aligned} &\mathrm{P}_{ij}^{p} = P_j^{p,min} + rand \times (P_j^{p,max} - P_j^{p,min}) \\ &j = 1, 2, \ldots N_p \end{aligned} \tag{13}$$

$$\begin{aligned} &\mathrm{P}_{ij}^{c} = P_j^{c,min}(.) + rand \times (P_j^{c,max}(.) - P_j^{c,min}(.)) \\ &j = 1, 2, \ldots, N_c \end{aligned} \tag{14}$$

$$\begin{aligned} &\mathrm{H}_{ij}^{c} = H_j^{c,min}(P_{ij}^c) + rand \times (H_j^{c,max}(P_{ij}^c) - H_j^{c,min}(P_{ij}^c)) \\ &j = 1, 2, ..., N_c \end{aligned} \tag{15}$$

$$\begin{aligned} &\mathrm{H}_{ij}^{h} = H_j^{h,min} + rand \times (H_j^{h,max} - H_j^{h,min}) \\ &j = 1, 2, .., N_h \end{aligned} \tag{16}$$

Step 3. Calculating the power of each country according to the objective cost function of the problem. In order to satisfy the equality constraints, the method of penalty coefficients has been used as follows:

$$\begin{aligned} \cos t = &\sum_{i=1}^{N_p} C_i(P_i^p) + \sum_{j=1}^{N_c} C_j(P_j^c, H_j^c) + \sum_{k=1}^{N_h} C_k(H_k^h) + \\ &w_1 \times abs\left(\sum_{i=1}^{N_p} P_i^p + \sum_{j=1}^{N_c} P_i^c - P_d - P_{loss} \right) + w_2 \times \\ &abs\left(\sum_{j=1}^{N_c} H_j^c + \sum_{k=1}^{N_h} H_k^h - H_d \right) \end{aligned} \tag{17}$$

Where w1 and w2 are the penalty coefficients. In this paper, w1=50, w2 = 30 is a proper setting.

Step 4. Definition of imperialists and empire formation.

Step 5. Moving the colonies of each empire towards their imperialist and exchange the position of a colony and the imperialist if it is stronger.

Step 6. If possible, the revolution will be carried out.

Step 7. Updating the $f_{\cos t}^{col,j}$, and $f_{\cos t}^{(imp,j)}$ for each set of country. Then, calculate the total cost using (12) for all empire. Finally, the empires compete with each other and if an empire will be collapsed in case it loses all its relevant colonies.

Step 8. Repeating the steps 5-7 as long as the number of iterations reaches $Iteration_{max}$. Otherwise, go to Step 9.

Step 9. Introducing the variables of the strongest imperialist and the relevant cost as the best solution.

5. COMPARISON OF NUMERICAL RESULTS OF DIFFERENT ALGORITHMS

Generally for testing a suggested metaheuristic algorithm performance, it should be implemented on some standard case systems. In this work we selected five case studies as the test study systems for verifying the performance and convergence of the suggested approach. It should be noted that these systems are generally has been used in the literature review. Furthermore the obtained simulation results are compared with the other proposed algorithms in this context which applied to this problem. In the first Test system, a simple and sample function in MATLAB software is chosen to show and illustrate the ability of the algorithm. In other test cases, which completely were reported before in the relevant references, in order to prove the efficiency and ability of the presented algorithm, the findings are detailed and the relevant results obtained by different algorithms were detailed in terms of objective cost function with other algorithms. It should be mentioned that all simulations are run 50 times. As an important note we should keep in the mind that none of the non-equality constraints are violated in these simulations. Also, the generation and load (plus the transmission ohmic losses in cases that the electrical losses are modeled) balance constraint can be easily checked by considering the total generated power and heat reported in these tables in order to ensure the constraint satisfaction.

The relevant data of the simulated case studies are depicted in Table 1. It should be mentioned that the detailed data can be easily find in ref. [18].

A. Test system 1

At the first section and in order to prove the proposed algorithm' ability, we considered the rosenbrock, which consists of two variables. General function of this optimization problem is as: $F_{rosenbrock}(x) = 100(x_1^2 - x_2)^2 + (x_1 - 1)^2$

Table 1. Case study data used in this work

CASE STUDY	DESCRIPTION
# 1	Rosenbrock Function in MATLAB software
# 2	5 units: one POU, 3 CHP units, and one HOU, ignoring the VPLE and transmission ohmic losses
# 3	7 units: 4 POUs, 2 CHP units, and one HOU, considering transmission ohmic losses based on B-Matrix and VPLE.
# 4	24 units: 13 POUs, 6 CHP units, and 5 HOUs, considering the VPLE
# 5	48 units: 26 POUs, 12 CHP units, and 10 HOUs.

Where $-10 \leq x_1, x_2 \leq 10$

The system consists of 38 countries including 5 imperialists and 33 colonies. Fig. 2 illustrates how the strongest imperialist forms as the final answer. In this figure, the imperialists are depicted in the form of stars where the colonies are shown in the form of some points. As can be seen from the figure, the powerless empires collapse with increasing number of iterations.


A) Position of colonies \& empires in first iteration
B) Position of colonies \& empires in 10th iteration

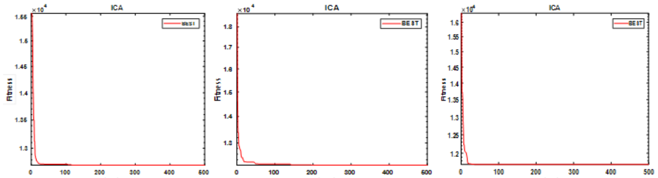

C) Position of colonies \& empires in 20th iteration
D) Position of colonies \& empires in 30th iteration

Fig. 2. The formation of the most powerful empire as the ultimate answer for Test system 1.

B. Test system 2

The simulation results found by the ICA are compared with the other addressed algorithms in this field. These algorithms (R1_C9) are concluding: HS [2], GA [2], EDHS [7], TVAC-PSO [18], EMA [6], RCGA-IMM [28], and CPSO [18]. It should be mentioned that different load profiles are considered in this regard, which are demonstrated in table 2.

The reported results show that the ICA algorithm is superior to other algorithms. Assuming the constant load level in one year, annual savings resulting from applying the proposed algorithm will be equal to 36,792 and 213,130.8$ in comparison with GSA [17] for load profiles 2, and 3, respectively. In the case of load profile 1, GSA [17] results in less cost, but equality constraints are not met. Furthermore the convergence curve of the proposed algorithm under studied conditions is displayed in Fig. 3.



a) load profile number 1
b) load profile number 2
c) load profile number 3

Fig. 3. Convergence curve of the suggested algorithm regarding studied case 2.

C. Test system 3

The respective demanded heat and power in this case are supposed to be equal to 150 MWth, and 600 MW, respectively. Table 3 shows the simulation results obtained from applying ICA algorithm. Also, the reported results regarding DE [1], PSO [1], EP [1], GSA [17], CPSO [18], TVAC-PSO [18], BCO [19], EMA [26], CSO [27], and RCGA [19] are detailed. It expresses that the proposed approach has the best results among the obtained results from all algorithms. Also, assuming the constant demanded load for all the year, annual savings resulting from applying the ICA algorithm will be equal to 148,657.2$ in compare to EMA [26]. Furthermore, the electrical transmission ohmic losses are the lowest value, as well. Fig. 4 demonstrates the convergence curve of the suggested algorithm.

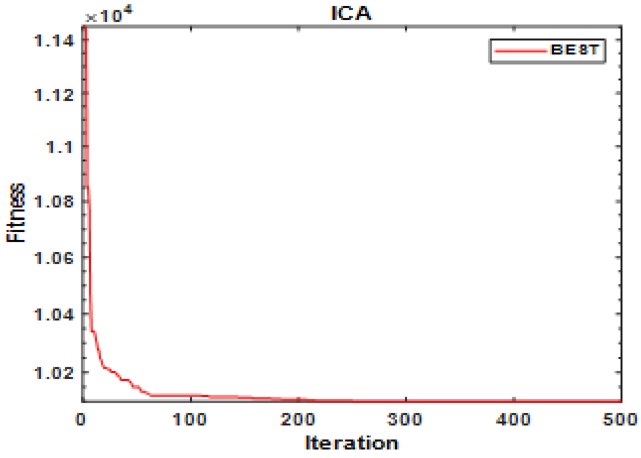


Fig. 4. Convergence curve of the suggested algorithm regarding case 3.

D. Test system 4

Total demanded heat is supposed to be equal to 1250 MWth. This item is assumed to be equal to 2350 MW for demanded power in this case. A comparison between the results of ICA and the other proposed algorithms in this field such as GSA [17], TVAC-PSO [18], EMA [26], CSO [27], RCGA-IMM [28], and CPSO [18] are presented in Table 4. It shows that the simulation results from the suggested algorithm are better than generally form the other introduced algorithms in this work The annual cost savings arising in the proposed method compared to CPSO [18], TVAC-PSO [18], RCGA-IMM [28], CSO [27], and GSA [17] are 16637868,

Table 2. Obtained numerical results for case 2

Method	P1	P2	P3	P4	H2	H3	H4	H5	Total Heat	Total Power	Total cost
GA [2]	135.0000	70.8100	10.8400	83.2800	80.5400	39.8100	0.0000	29.6400	149.99	299.93	13779.5
HS [2]	134.7400	48.2000	16.2300	100.8500	81.0900	23.9200	6.2900	38.7000	150.00	300.02	13723.2
EDHS [7]	135.0000	18.1563	13.0749	133.7688	84.0626	37.7657	0.0000	28.1118	149.94	300.00	13613.0*
CPSO [18]	135.0000	40.7309	19.2728	105.0000	64.4003	26.4119	0.0000	59.1955	150.01	300.00	13692.5
TVAC-PSO [18]	135.0000	41.4019	18.5981	105.0000	73.3562	37.4295	0.0000	39.2143	150.00	300.00	13672.8
RCGA-IMM [28]	135.0000	40.7680	19.2320	105.0000	73.5960	36.7760	0.0000	39.6280	150.00	300.00	13660.5*
EMA [26]	135.0000	40.7163	19.2837	105.0000	73.7022	36.7183	0.0000	39.5829	150.00	300.00	13672.74
GSA [17]	135.0000	41.7806	18.1736	105.0000	74.0890	37.3336	0.0000	38.5713	149.99	299.95	13671.1
ICA	135.0000	40.7485	19.2315	105.0000	73.5948	36.7809	0.0000	39.6242	150.00	299.98	13671.62
Power = 300 MW Load profile number 1 Heat = 150 MWth											
GA [2]	119.2200	45.1200	15.8200	69.8900	78.9400	22.6300	18.4000	54.9900	174.96	250.05	12327.3
HS [2]	134.6700	52.9900	10.1100	52.2300	85.6900	39.7300	4.1800	45.4000	175.00	250.00	12284.4
EDHS [7]	135.0000	0.112	0.0000	114.8888	85.8178	56.3198	0.0000	32.8135	174.95	250.00	11836.0*
CPSO [18]	135.0000	40.3446	10.0506	64.6060	70.9318	39.9918	4.0773	60.0000	175.00	250.00	12132.8
TVAC-PSO [18]	135.0000	40.0118	10.0391	64.9491	74.8263	39.8443	16.1867	44.1428	175.00	250.00	12117.3
RCGA-IMM [28]	135.0000	40.0000	10.0000	65.0000	75.0000	40.0000	14.0595	45.9405	175.00	250.00	12104.8*
EMA [26]	135.0000	40.0000	10.0002	64.9997	74.9980	40.0001	14.0624	45.9394	175.00	250.00	12117.07
GSA [17]	135.0000	39.9998	10.0000	64.9807	74.9844	40.0000	17.8939	42.1095	174.99	249.98	12117.3
ICA	135.0000	40.0000	10.0000	65.0000	75.0000	40.0000	15.6360	44.3640	175.00	250.00	12113.1
Power = 250 MW Load profile number 2 Heat = 175 MWth											
GA [2]	37.9800	76.3900	10.4100	35.0300	106.0000	38.3700	15.8400	59.9700	220.18	159.81	11837.4
HS [2]	41.4100	66.6100	10.5900	41.3900	97.7300	40.2300	22.8300	59.2100	220.00	160.00	11810.8
EDHS [7]	135.0000	0.0000	0.0000	25.0000	87.2560	58.1586	40.1823	34.3703	219.97	160.00	93181.0*
CPSO [18]	35.5972	57.3554	10.0070	57.0587	89.9767	40.0025	30.0232	60.0000	220.00	160.02	11781.3
TVAC-PSO [18]	42.1433	64.6271	10.0001	43.2295	96.2593	40.0001	23.7407	60.0000	220.00	160.00	11758.0
RCGA-IMM [28]	42.1660	64.6523	10.0000	43.1817	96.2810	40.0000	23.7190	60.0000	220.00	160.00	11758.63
EMA [26]	42.1433	64.6378	10.0000	43.2188	96.2653	40.0000	23.7338	60.0000	220.00	160.00	11757.91
GSA [17]	39.2183	60.1454	10.0000	50.6296	82.8700	40.0000	27.1044	60.0000	209.97	159.99	11745.5
ICA	40.4278	60.0402	10.0373	49.4947	93.3952	40.0160	26.5888	60.0000	220.00	160.00	11721.17
Power = 160 MW Load profile number 3 Heat = 220 MWth											

*invalid

Table 3. Obtained numerical results for case 3.

Generation	EP [1]	PSO [1]	DE [1]	GSA [17]	CPSO [18]	TVAC-PSO [18]	CSO [27]	EMA [26]	BCO [19]	RCGA [19]	Proposed ICA
p1	61.3610	18.4626	44.2118	48.7638	75.0000	47.3383	45.4909	52.6847	43.9457	74.6834	45.5941
p2	95.1205	124.2602	98.5383	98.7469	112.3800	98.5398	98.5398	98.5398	98.5882	97.9578	98.5412
p3	99.9427	112.7794	122.6913	112.0000	30.0000	112.6735	112.6734	112.6734	112.9320	167.2308	112.6723
p4	208.7319	209.8158	209.7741	208.5113	250.0000	209.8158	209.8158	209.8158	209.7719	124.9079	209.8248
p5	98.8000	98.8140	98.8217	92.6909	93.2701	92.3718	94.1838	93.8341	98.8000	98.8008	94.0712
p6	44.0000	44.0107	44.0000	40.0000	40.1585	40.0000	40.0000	40.0000	44.0000	44.0001	40.0000
h5	18.0713	57.9236	12.5379	35.9704	32.5655	37.8467	27.1786	29.2420	12.0974	58.0965	27.8510
h6	77.5548	32.7603	78.3481	75.0000	72.6738	74.9999	75.0000	75.0000	78.0326	32.4116	75.0010
h7	54.3739	59.3161	59.1139	39.0000	44.7606	37.1532	47.8214	45.7579	59.8790	59.4919	47.1380
ploss	7.9561	8.1427	8.0372	0.7128	0.8086	0.73921	0.7037	7.5479	8.0384	7.5808	0.7036
Total cost	10390	10613	10317	9912.691	10325.33	10100.311	10094.1	10111.07	10317	10667	10094.1
Total Power	607.9561	608.1427	608.0372	600.7129	600.8086	600.7392	600.7037	607.5479	608.038	607.5808	600.7036
Total Heat	150	150	149.99	149.97	149.99	150.00	150.00	150.00	150	150	149.99

*Invalid

2503432.8, 794794.8, 614514, and 2495724$, respectively. Fig. 5, shows the convergence curve of this case.

At the last four rows of this table, the minimum, maximum, mean, and standard deviation costs of different algorithms applying the CHPED problem are reported. It is clear that the ICA can be mentioned as a superior evolutionary algorithm in solving the complex, non-liner and non-convex problems, such as CHPED.

One of the most important features regarding the evolutionary algorithms, such as ICA, is due to selecting the algorithm parameters, or parameter setting. As it was demonstrated in the previous sections, different references have proposed different strategies for setting the algorithm parameters. Here, and in order to clarify this task, a brief sensitivity analysis regarding the ICA parameters is reported. As a solution, the sensitivity of the obtained results to different values of the ICA parameters are studied. A summary of results are given in Table 5. As it is shown in this Table, the best parameter setting to obtain the optimal results in a reasonable time is demonstrated in the third row of this Table. It should be mentioned that we applied these preferred values as the parameter setting in this paper.

E. Test system 5

The total demanded power is assumed to be 4700 MW and total demanded heat is supposed to be equal to 2500 MWth [17].

Table 6 describes the results obtained from the proposed method, CPSO [18], TVAC-PSO [18], CSO [27], and GSA [17]. The annual cost that the proposed method can save compared to CPSO, TVAC-PSO, CSO [27], and GSA algorithms is 35880530.76, 19377566.76, 3108669.96, and 14487734.76 $, respectively. Fig. 6 indicates the convergence characteristic curve of the suggested algorithm.

6. CONCLUSION

This paper focused on solving the CHPED problem by proposing a new approach known as ICA. As the literature confirms, this is the first time that the ICA has been adopted to the mentioned problem. The presented approach takes into account the VPLE as well as electrical transmission ohmic losses. Its performance and effectiveness were verified by applying to five test case and comparing its numerical results with other algorithms showed the ability of the mentioned algorithm to find the optimal solution. As it was detailed in the simulation case studies, ICA has the ability in finding the optimal operation points in comparing the other well-known algorithms which were suggested before in this field. In the future plan, completing the CHPED problem concluding the other real-world conditions such as the prohibited zones and ramp rate limits should mentioned in the problem formulation. Furthermore, applying the proposed algorithm to solve some multi-objective sophisticated CHPED problems should be studied in detail.

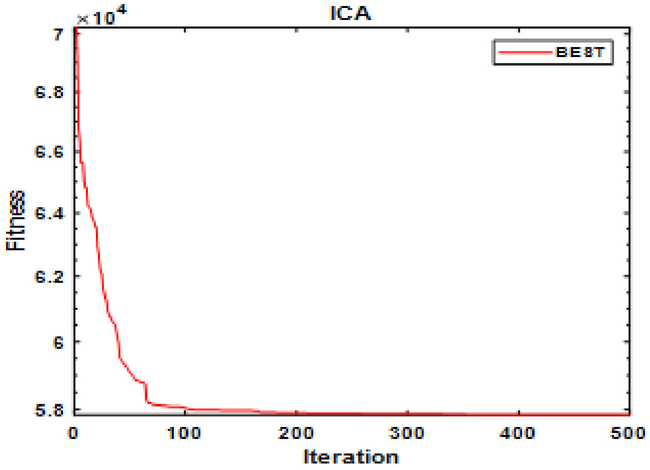


Fig. 5. Convergence curve of the suggested algorithm regarding case system 4

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Table 4. Obtained numerical results regarding case 4.

Generation	GSA [17]	TVAC-PSO [18]	CPSO [18]	EMA [26]	RCGA-IMM [28]	CSO [27]	Proposed Algorithm (ICA)
P1	538.5150	538.5587	680.0000	628.3171	448.8000	448.7991	538.5635
P2	224.4727	224.4608	0.0000	299.1859	299.9568	225.2383	299.205
P3	224.4611	224.4608	0.0000	299.1624	299.2108	299.2013	299.205
P4	109.8666	109.8666	180.0000	109.8665	109.8694	109.8668	109.8701
P5	109.8666	109.8666	180.0000	109.8605	109.8679	109.8666	109.8701
P6	109.9000	109.8666	180.0000	109.8650	159.7353	159.7323	109.8701
P7	109.8666	109.8666	180.0000	60.0000	109.8684	159.7311	109.8699
P8	109.8666	109.8666	180.0000	109.8664	60.6545	159.7311	109.8699
P9	109.8666	109.8666	180.0000	109.8564	159.7354	109.8666	109.8701
P10	77.5210	77.5210	50.5304	40.0000	75.8146	40.0001	77.4001
P11	77.5341	77.5210	50.5304	77.0195	40.1672	77.3999	77.4001
P12	120.0000	120.0000	55.0000	55.0000	92.6079	92.3999	55.0031
P13	120.0000	120.0000	55.0000	55.0000	92.4045	55.0000	55.0030
P14	92.5632	88.3514	117.4854	81.0000	83.0376	87.5549	81.9890
P15	40.0050	40.5611	45.9281	40.0000	40.0071	40.0000	40.0080
P16	84.4916	88.3514	117.4854	81.0000	81.4577	90.6099	82.0060
P17	40.0079	40.5611	45.9281	40.0000	41.6937	40.0000	40.0080
P18	10.0000	10.0245	10.0013	10.0000	10.0042	10.0000	10.0010
P19	41.1998	40.4288	42.1109	35.0000	35.1058	35.0001	35.017
H14	111.2790	108.9256	125.2754	104.8002	105.9431	108.4786	105.35
H15	74.9980	75.4844	80.1175	75.0000	75.0059	75.0000	75.008
H16	106.7495	108.9256	125.2754	104.8002	105.0550	110.1931	105.36
H17	74.9978	75.4840	80.1174	75.0000	76.4619	75.0000	75.0070
H18	40.0000	40.0104	40.0005	40.0000	40.0007	40.0000	40.00
H19	22.8181	22.4676	23.2322	20.0000	20.0477	20.0000	20.007
H20	458.8811	458.7020	415.9815	470.3996	467.4871	461.3296	469.26
H21	60.0000	60.0000	60.0000	60.0000	59.9999	59.9999	59.9990
H22	60.0000	60.0000	60.0000	60.0000	59.9997	59.9999	59.9990
H23	120.0000	120.0000	120.0000	120.0000	119.9991	119.9989	120.0000
H24	120.0000	120.0000	120.0000	120.0000	119.9998	120.0000	120.0000
Min cost	58121.86	58122.74	59736.26	57825.47	57927.69	57907.11	57836.96
Mean cost	NA	58198.31	59853.47	57832.73	58066.63	57908.31	57848.89
Max cost	NA	58359.55	60076.69	57841.14	58301.90	57911.95	57879.51
standard deviation	NA	NA	NA	NA	NA	1.3871	20.6368

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Table 6. Obtained numerical results for case 5.

GENERATION	CPSO [18]	TVAC-PSO [18]	GSA [17]	CSO [27]	PROPOSED ICA	GENERATION	CPSO [18]	TVAC-PSO [18]	GSA [17]	CSO [27]	PROPOSED ICA
P1	359.0392	538.5587	359.8656	538.5512	628.3181	P31	10.0002	10.0031	10.0000	10.0000	10.0008
P2	74.5831	75.1340	227.2336	224.4094	224.3154	P32	56.7153	35.0000	35.0000	35.0003	35.0020
P3	74.5831	75.1340	152.7852	224.4313	298.7944	P33	109.1877	95.4799	81.0020	81.4693	81.0064
P4	139.3803	140.6146	160.4948	159.7336	109.8615	P34	65.6006	54.9235	41.9658	40.0000	40.0016
P5	139.3803	140.6146	109.5165	60.0128	109.8659	P35	109.1877	95.4799	81.0020	81.0691	81.0064
P6	139.3803	140.6146	159.3399	60.0051	109.8499	P36	65.6006	54.9235	46.6684	40.0000	40.0016
P7	139.3803	140.6146	162.1068	109.8705	109.8591	P37	10.6158	23.4981	10.0000	10.0007	10.0008
P8	139.3803	140.6146	109.5873	109.8672	109.8644	P38	60.5994	54.0882	90.0000	35.0000	35.0019
P9	139.3803	140.6146	158.9737	159.7445	109.8648	H27	111.4458	108.1177	110.5296	105.9126	104.8000
P10	74.7998	112.1998	113.3540	114.8100	40.0011	H28	125.6898	88.9006	74.9844	75.0000	75.0017
P11	74.7998	112.1998	114.9745	77.4097	40.0011	H29	111.4458	108.1177	104.7869	105.0423	104.8000
P12	74.7998	74.7999	55.3445	55.0031	55.0011	H30	125.6898	88.9006	74.8787	75.0000	75.0017
P13	74.7998	74.7999	120.0000	55.0000	55.0011	H31	40.0001	40.0013	40.0000	40.0000	39.9999
P14	679.8810	269.2794	361.9144	628.3206	628.3182	H32	29.8706	20.0000	19.0125	20.0000	20.0003
P15	148.6585	299.1993	223.9861	149.6535	298.8581	H33	120.6188	112.9260	104.7912	105.0634	104.8000
P16	148.6585	299.1993	241.2574	360.0000	299.1346	H34	97.0997	87.8827	76.6806	75.0000	75.0017
P17	139.0809	140.3973	159.8437	109.8693	109.8659	H35	120.6188	112.9260	104.7912	104.8372	104.8000
P18	139.0809	140.3973	159.0831	60.0014	109.8663	H36	97.0997	87.8827	80.7377	75.0000	75.0017
P19	139.0809	140.3973	110.7600	109.8408	109.8653	H37	40.2639	45.7849	40.0000	40.0000	39.9999
P20	139.0809	140.3973	108.1711	159.7348	109.8648	H38	31.6361	28.7665	45.0000	20.0000	20.0003
P21	139.0809	140.3973	165.0457	159.7384	109.8577	H39	357.9456	433.9113	488.8361	464.9032	470.6267
P22	139.0809	140.3973	160.8239	60.0000	159.7277	H40	59.9916	60.0000	60.0000	59.9999	59.9993
P23	74.7998	74.7998	98.8179	77.4041	40.0011	H41	59.9916	60.0000	60.0000	60.0000	59.9993
P24	74.7998	74.7998	83.8242	114.8152	40.0011	H42	120.0000	120.0000	120.0000	119.9994	119.9991
P25	112.1993	112.1997	55.0000	92.4040	55.0011	H43	120.0000	120.0000	120.0000	119.9999	119.9991
P26	112.1993	112.1997	120.0000	92.4144	55.0011	H44	370.6214	415.9741	415.0132	474.2431	470.1713
P27	92.8423	86.9119	91.2279	82.9843	81.0064	H45	59.9999	60.0000	60.0000	59.9997	59.9993
P28	98.7199	56.1027	39.9998	40.0000	40.0016	H46	59.9999	60.0000	60.0000	59.9998	59.9993
P29	92.8423	86.9119	81.0027	81.4314	81.0064	H47	119.9856	119.9989	120.0000	119.9997	119.9991
P30	98.7199	56.1027	40.0072	40.0000	40.0016	H48	119.9856	119.9989	120.0000	119.9998	119.9991

Algorithm	CPSO [18]	TVAC-PSO [18]	GSA [17]	CSO [27]	Proposed ICA
Total Cost	119708.8	117824.9	117266.7	115967.72	115612.849

Table 5. Analysis the sensitivity of the results to parameters of algorithms for case 4.

State	Iterationmax	$N_{country}$	N_{imp}	β	ξ	Minimum cost	Average cost	Time(s)
1	500	100	1	2	0.1	58087.45	58100.24	39.2
2	500	100	5	2	0.1	57881.26	57924.57	39.4
3	500	100	10	2	0.1	57836.96	57851.23	39.4
4	500	100	50	2	0.1	57869.13	57986.68	39.8
5	500	200	20	2	0.1	57837.85	57856.85	76.3
6	500	300	30	2	0.1	57836.49	57855.55	92.5
7	500	400	40	2	0.1	57836.45	57857.72	112.7
8	500	50	5	2	0.1	58851.84	59002.41	23.8
9	500	100	10	1	0.1	58820.53	58826.63	38.9
10	500	100	10	3	0.1	58415.88	58963.25	39.1
11	500	100	10	2	0.5	57876.55	57914.04	38.8
12	500	100	10	2	0.01	57906.10	57986.74	39.0
13	100	100	10	2	0.1	58059.07	58957.80	10.8
14	1000	100	10	2	0.1	57838.32	57846.74	78.6

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