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Applications of PSO Variants for Combined Heat and Power Dispatch Problem

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Abstract

This paper presents the applications of Particle Swarm Optimization (PSO) variants for finding optimal solutions of combined heat and power dispatch problem. In the problem, the objective is to minimize the total fuel cost of producing power energy and heat energy of co-generators, pure heat generators and pure power generators. Different PSO variants including conventional PSO are run for solving systems with the presence of the three types of generators. The comparisons with previous methods and with other PSO versions indicate that the applied PSO variants have a high performance for the problem. As a result, it concludes that these methods should be used for the problem.

Keywords: Particle Swarm Optimization, co-generators, pure heat generators, pure power generators, fuel cost, power energy, heat energy.

1. Introduction

Nowadays, the power output of the thermal power plant still accounts for a majority of generation sources. The working principle of such plants is to use fossil fuels, including oil, coal, and gas to produce electricity for meeting load demand. Generally, the efficiency of thermal power plant is only 50-60% because a huge volume of heat released is wasted. For improving the efficiency of the thermal power plant, one of the best ways use the combined heat and power economic load dispatch (CHPED). In CHPED problem, excess heat mentioned is used for heating demand or many different industrial applications. There are numerous studies proposed to deal with this problem such as Harmony search algorithm (HSA) and its modified versions [1-3], Two-layer algorithm (TLA) [4], genetic algorithm (GA) and its improved versions [5-7], Teaching learning based optimization (TLBO) [8], Sequential quadratic programing (SQP) [9], Dual programing (DP) [10], Bee colony optimization [11], Improved ant colony search algorithm (IACSA) [12], Evolutionary programing (EP) [13], Mesh adaptive direct search algorithm (MADSA) [14], Direct search method (DSM) [15], Artificial immune system (AIS) [16], Lagrangian relaxation with surrogate sub-gradient multiplier updates [17], The derivative versions of Particle swarm optimization (PSO) [18-25]

In this paper, the authors used particle swarm optimization (PSO) algorithm and two improved versions of PSO such as Time varying inertia weigh particle swarm optimization (TVIW_PSO) and to find out the optimal results for the CHPED problem. The main target of CHPED problem is to minimize the total fuel cost for all generators in system. Three applied methods' performance is tested by using three different cases. Specifically, three cases use the same system with one pure power unit, two combined heat and power units, and one pure heat unit and different constraints but the load demand are different.

The main contribution of this paper is:

- Proposed and applied successfully two improved versions of PSO for the CHPED problem
- The optimal results given by the TVIW_PSO_CD not only better than the original PSO but also outstanding while compared with the other methods. In addition, all important constraints are satisfied during the process of solving the CHPED problem.
- This paper also diversifies the reference source for later research.

All of works is implemented in a personal computer with 2.6 GHz of processing unit and 8 GB of RAM

2. Headings and Footnotes

2.1 Objective function

The main target of the CHPED problem allocates the amount of power and heat produced by generators in order to reduce the total fuel cost by minimum value. Besides, the working limitation belonging all type of generators, the power demand and the heat demand must be all satisfied. There are three types of generators considered in this problem, they are power dedicated generators, heat generators and the combined generators which can produce both power and heat. The quantities for each type of these generators is denoted as N_{pp}, N_{ph} and N_c, respectively. The description for the main target of the CHPED problem is presented as below:

$$Minimize\ F = \sum_{i=1}^{N_{PP}} F_{pi}(P_{pi}) + \sum_{k=1}^{N_{Ph}} F_{hk}(H_{hk}) + \sum_{j=1}^{N_c} F_{cj}(P_{cj}, H_{cj}) \tag{1}$$

- The fuel cost of power generator is described approximately as a quadratic function as below:

$$F_{pi}\left(P_{pi}\right) = a_{pi} + b_{pi}P_{pi} + c_{pi}P_{pi}^2 \tag{2}$$

where, a_{pi}, b_{pi} and c_{pi} are the fuel consumed coefficients of the dedicated power generator; P_{pi} is the power bulk generated.

- The fuel cost for heat generator is also described in the same form as the power dedicated generator one.

$$F_{hk}\ (H_{hk}) = a_{hk} + b_{hk}H_{hk} + c_{hk}H_{hk}^2 \tag{4}$$

where, a_{hk}, b_{hk} and c_{hk} are fuel coefficients of the heat generators; H_{hk} is the amount of heat generated by the heat generators.

- The fuel cost mathematical expression of the combined generator is a combination of the two separate quadratic functions as below:

$$F_{cj}\left(P_{cj}, H_{cj}\right) = a_{cj} + b_{cj}P_{cj} + c_{cj}P_{cj}^2 + \ k_{cj} + l_{cj}H_{cj}^2 + m_{cj}H_{cj}P_{cj} \tag{5}$$

where, P_{cj} and H_{cj} are the amount of power and heat generated by the combined generators respectively; a_{cj}, b_{cj}, c_{cj}, k_{cj}, l_{cj} and m_{cj} are the fuel coefficients

2.2 Constraints

These constraints considered in CHPED problem are classified into two types: The physical constraints and balance constraints. The physical constraints are mainly regarding the working limitation of generators while the balance constraints are aiming to create a parity between supply side and demand side. The details about each type of constraints is depicted as below:

2.2.1 The working constraints of generator

Due to the CHPED considers three types of generator, therefore there are three types of working constraints that need to respects strictly. They are the working constraints belonged the dedicated power generators, the heat generator and the combined generators. Explicitly, the amount of power generated by dedicated power generator must be located inside the lower boundary and the upper boundary as modeled in the equation below.

$$P_{pi,min} \le P_{pi} \le P_{pi,max} \tag{6}$$

Similarly, the working constraint of heat generator is all about the amount of heat produced and its mathematical model is described as follows:

$$H_{hk,min} \le H_{hk} \le H_{hk,max} \tag{9}$$

Finally, the working constraints of combined generator are regarding the ability to producing the bulk of heat and power within its restrictions. The mathematical expression of this constraints is presented as below

$$P(H_{cj}) \leq P_{cj} \leq P_{cj,max}(H_{cj}) \tag{7}$$

$$H_{cj,min}(P_{cj}) \leq H_{cj} \leq H_{cj,max}(P_{cj}) \tag{8}$$

2.2.2 The power balance constraints

This constraint is regarding the relationship between the amount of consumed by load, the total power produced by all generators in system and the amount of power loss in transmission lines. This relationship is illustrated by the Equation (10) below:

$$P_D+P_L-\sum_{i=1}^{N_{PP}} P_{pi}-\sum_{j=1}^{N_c} P_{cj}=0 \tag{10}$$

And, the power loss is calculated by using the Equation 11 below

$$P_L=\sum_{i=1}^{N_{pp}+N_c}\sum_{j=1}^{N_{pp}+N_c} P_iB_{ij}P_j+\sum_{i=1}^{N_{pp}+N_c} B_{0i}P_i+B_{00} \tag{11}$$

Where, P_i and P_j are respectively represented for the power bulk injected at node *i* and node *j*; B_{ij}, B_{0i} and B_{00} are loss coefficients picked up from loss matrix

2.2.3 The heat balance constraints

Similar to the power balance constraint, these constraints depict the correlation between the heat supply side and the consuming side that they must be equal. The constraint is formulated as follows:

$$H_D-\sum_{j=1}^{N_c} H_{cj}-\sum_{k=1}^{N_{ph}} H_{hk}=0 \tag{12}$$

3. Methods

3.1 Particle swarm optimization

The particle swarm optimization (PSO) was introduced for the first time in 1995 by Kenedy and Eberhart. This method presented a new approach to deal with the optimal problems. The PSO requires a particular number of individual that each individual is identified by its own position and velocity. The mathematical model of the identification for every single individual is presented at follows:

$$Y_i^{new}=Y_i+n_1\times rd\times\left(X_{Best,i}-X_i\right)+n_2\times rd(X_{G\_best}-X_i) \tag{17}$$

$$X_i^{new}=X_i+Y_i^{new} \tag{18}$$

where, Y_i^{new} , Y_i are the new velocity and the old velocity of the individual *i*, respectively. n_1 and n_2 are the accelerate coefficient, *rd* is the random value picked up from the interval of 0 and 1. $X_{Best,i}$ is the best position of the individual *i* at the moment considered. X_{G_best} is the best position of all individual in group.

3.2 PSO with time varying coefficient and inertia weight factor

Many improved versions of PSO were proposed to enhance the efficiency of the original PSO [21-25]. One of them is TVIW_PSO. TVIW_PSO has been built based on the PSO with Tightening coefficient (TFPSO) [22] and the Inertia weigh PSO (IW-PSO) [24]. In this new method, a factor called inertia weigh (*IW*) is added into the new velocity update equation as follows:

$$Y_i^{new} = TF \times (IW \times Y_i + n_1 \times rd \times \left(X_{Best,i} - X_i\right) + n_2 \times rd\left(X_{G_{best}} - X_i\right)) \tag{20}$$

where, the inertia weight factor (*IW*) and the tightening coefficient (*TF*) are calculated as follows:

$$IW = IW_{max} \times \frac{IW_{max} - IW_{min}}{IW_{max}} \times iter \tag{21}$$

$$TF = \frac{2}{\left|2 - (n_1 + n_2) - \sqrt{(n_1 + n_2)^2 + 4 \times (n_1 + n_2)}\right|} \tag{22}$$

This modified version of the original PSO have no difference in the update new position for each individual.

3.3 TVIW_PSO with Cauchy distribution

This modification of PSO is also aim to improve the new velocity update procedure for each individual. By applying the Cauchy distribution and inheriting the foundation of the previous modification as mentioned at subsection 3.2, a new method named TVIW_PSO_CD is built. The presence of Cauchy distribution in this modification plays a role as a coefficient in order to support for the new velocity update procedure. The determination of this coefficient is described below:

$$CD = \left|tan\left(\frac{\pi}{4} \times (rand - \frac{1}{2})\right)\right| \tag{23}$$

The presence the new coefficient derived from Cauchy distribution (CD) [24] in the new velocity update procedure of the TVIW_PSO_CD is described as follows:

$$V_i^{new} = TF \times (\omega \times V_i + c_1 \times rand \times CD \times (P_{Best,i} - P_i) + c_2 \times rand \times (P_{Gbest,i} - P_i)) \tag{24}$$

To insert “Tables” or “Figures”, please paste the data as stated below. All tables and figures must be given sequential numbers (1, 2, 3, etc.) and have a caption placed below the figure (“FigCaption”) or above the table(“FigTalbe”) being described, using 8pt font and please make use of the specified style “caption” from the drop-down menu of style categories

4. Results

Three versions of PSO are applied to solve the CHPED problem with different loads. The system information is taken from [19]. Power generation and heat generation constraints of the system are illustrated as Figure 1. It is not quite hard to realize that there is the mutual interaction between the amount of power and heat generated belonging the combined generator in CHPED problem. Three methods are operated with population and maximum iteration are set to 50 and 200, respectively for all cases.

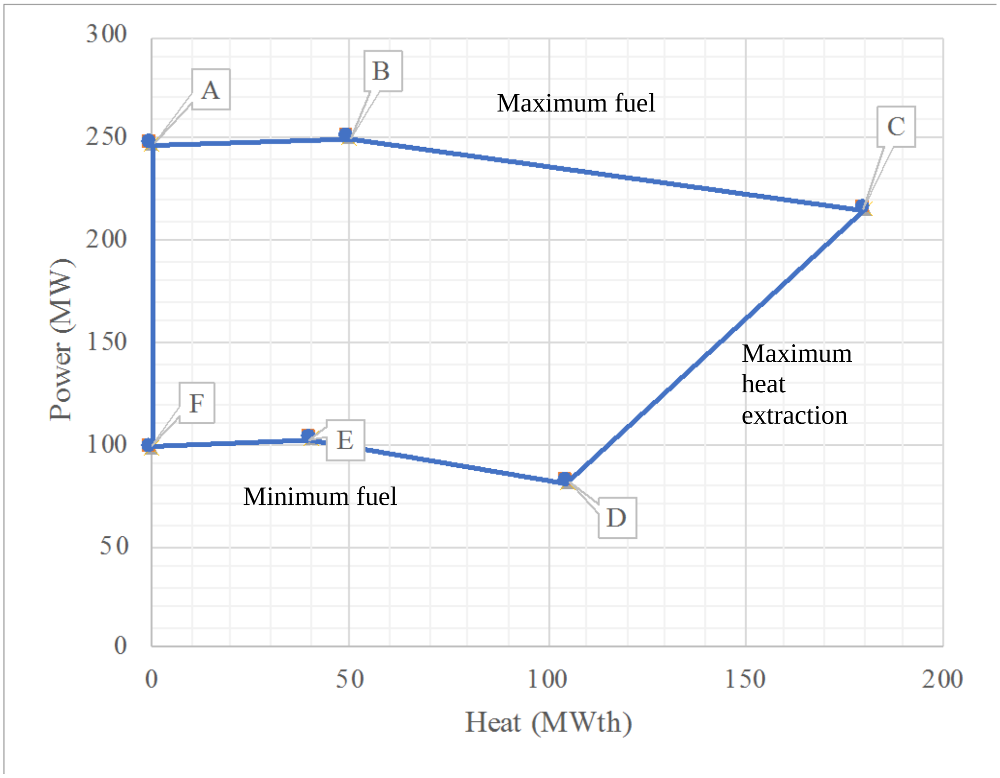

Fig. 1 Safety working boundaries of the combined generator.

4.1 Case 1

In this case, three methods are applied to solve the CHPED problem with power demand of 200 MW and heat demand of 115 MWth. Results obtained in Table 1 show that, the TVIW_PSO and TVIW_PSO_CD is better than the original PSO in all aspect considered such as minimum cost value (Min.cost), mean cost value (Mean.cost), the maximum cost value (Max.cost) and standard deviation (Std). The Min.cost obtained by TVIW_PSO_CD and TVIW_PSO are 9257.075 $/h whist the similar number given by the original PSO is 9257.0753 $/h. The Mean.cost of TVIW_PSO_CD method is 9257.0808($/h) while the similar ones reached by TVIW_PSO method and original PSO method are 9267.507 $/h and 9278.094 $/h. Regarding the Max.cost, TVIW_PSO_CD method also obtains the value less than the TVIW_PSO method and the original PSO method. Explicitly, the maximum result obtained by TVIW_PSO_CD method is 9257.1702 $/h whist the similar ones given by TVIW_PSO method and the original PSO method reached the same value 9778.675$/h. It can be seen that the TVIW_PSO_CD method can find better optimal results than two others. Specifically, the mean cost value obtained by TVIW_PSO_CD method is less than the value given by both TVIWPSO method and the original PSO method by 10.43($/h) and 21.013($/h), respectively equal the improvement 0.11% and 0.22%, respectively. In term of the Max.cost, the number given by TVIW_PSO_CD method is also less than two other methods. Explicitly, 521.505($/h) for both TVIW_PSO method and original PSO method.

Table 1: The results obtained in Case 1

Method	**PSO**	**TVIW_PSO**	**TVIW_PSO_CD**
Min.cost	9257.0753	9257.0750	9257.0750
Mean.cost	9278.0940	9267.5070	9257.0808
Max.cost	9778.6750	9778.6750	9257.1702
Std	103.22	73.77	0.02

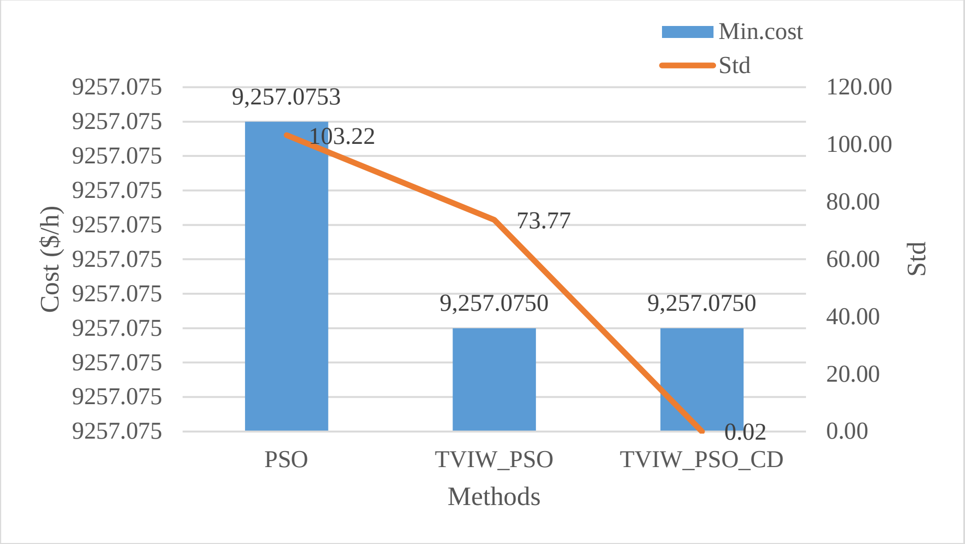

Fig. 2 The Min.cost and Std obtained by three methods in Case 1.

The observation from the orange line of the Fig 2 shows that TVIW_PSO_CD is the most effective method with the extremely impressive Std value only 0.02. The TVIW_PSO method placed at rank number 2 with the Std value is 73.77. The original PSO method is the worst method for solving the problem considered because its Std value is up to 103.22, extremely higher than two others in the Table 1. It can be concluded that TVIW_PSO_CD method is the most stable method among three methods applied for solving the problem considered in this case.

Table 2: The comparison with the other methods in Case 1

Method	**Min. cost ($/h)**	**Method**	**Min. cost ($/h)**
HSA [1]	9,257.07	LCPSO [19]	9257.075
LR [4]	9,257.10	LCPSO-CD [19]	9257.075
GA [5]	9,267.20	LWPSO [19]	9257.075
IACSA [6]	9,452.20	LWPSO-CD [19]	9257.075
EP [7]	9,257.10	GCPSO [19]	9257.075
IGA-MU [8]	9,257.08	GCPSO-CD [19]	9257.075
MADS–LHS [14]	9277.1311	GWPSO [19]	9257.075
MADS–PSO [14]	9301.3567	GWPSO-CD [19]	9257.075
MADS–DACE [14]	9257.0754	PSO	9257.075

NDS[15]	9,257.07	TVIW_PSO	9257.075
LRSS [17]	9,257.07	TVIW_PSO_CD	9257.075

The results obtained by three methods applied in this case are also compared with the other meta-heuristic methods listed in Table 2. The result given TVIW_PSO_CD are noticeably better than many other methods such as: HSA [1], LR [4], GA [5], IACSA [6], EP [7], IGA-MU [8], MADS–LHS [14], MADS–PSO [14]. Specifically, the Min.cost value given by the TVIW_PSO_CD is 9257.075 $/h while the similar numbers reported by the other methods are 9,257.07 $/h, 9,257.10 $/h, 9,267.20 $/h, 9,257.10 $/h, 9,257.08 $/h, 9277.1311 $/h, 9301.3567 $/h. In addition, the NDS [15], LRSS [17] and the other methods based PSO remaining in Table 3 all reports the same value equal all three method used in this case of study.

4.2 Case 2

In this case, power demand and heat demand are 175 MW and 110 MWth. This case also using the same data system as case 1. The results from Table 3 show that both TVIW_PSO_CD method and TVIW_PSO method reach the same Min.cost 8555.963 $/h while this kind of value reached by the original PSO is 8556,756 $/h. Therefore, the two modified PSO methods are better than the original PSO. In term of Mean.cost, the best value is belonged to the TVIW_PSO_CD method with 8555.998 $/h, the second best value is owned TVIW_PSO_CD method with 8565,594 $/h and the worst value is belonged the original PSO method with 8604.841 $/h. Take a look into the Max.cost, the TVIW_PSO_CD method stills the most effective method with 8556.641 $/h while the similar values of TVIW_PSO method and original PSO method are 8907.830 $/h and 9352.704 $/h, respectively. While considering the Std, the performance of TVIW_PSO_CD is also ranked number one with 0.1 and the original PSO is continuously the worst method with 143.4 of Std value. Hence, TVIW_PSO_CD method proved its high performance among other methods in this case. Especially, the set of results reached by TVIW_PSO_CD method are completely outstanding as comparing with the original PSO at all aspects. That means, the optimal results obtained by TIVW_PSO_CD method are less than the similar ones reached by the original PSO method. Specifically, 8558.963 $/h and 8556.756 $/h for Min.cost, 8555.998 $/h and 8604.841 $/h for the Mean.cost, 8556.641 $/h and 9352.704 $/h for the Max.cost and 0.1 and 143.4 for the Std. The exact numbers regarding how well the TVIW_PSO_CD method are better than the original PSO method about Min.cost, Mean.cost, Max.cost value and Std are 0.783 $/h, 48.8432 $/h, 796.063 $/h and 143.3, respectively. These number are respectively equal 0.0009 %, 0.57%, 8.51% and 99.93% of the improvement.

Table 3: The results obtained in Case 2

Method	**PSO**	**TVIW_PSO**	**TVIW_PSO_CD**
Min.cost	8556.746	8555.963	8555.963
Mean.cost	8604.841	8565.594	8555.998
Max.cost	9352.704	8907.830	8556.641
Std	143.4	51.1	0.1

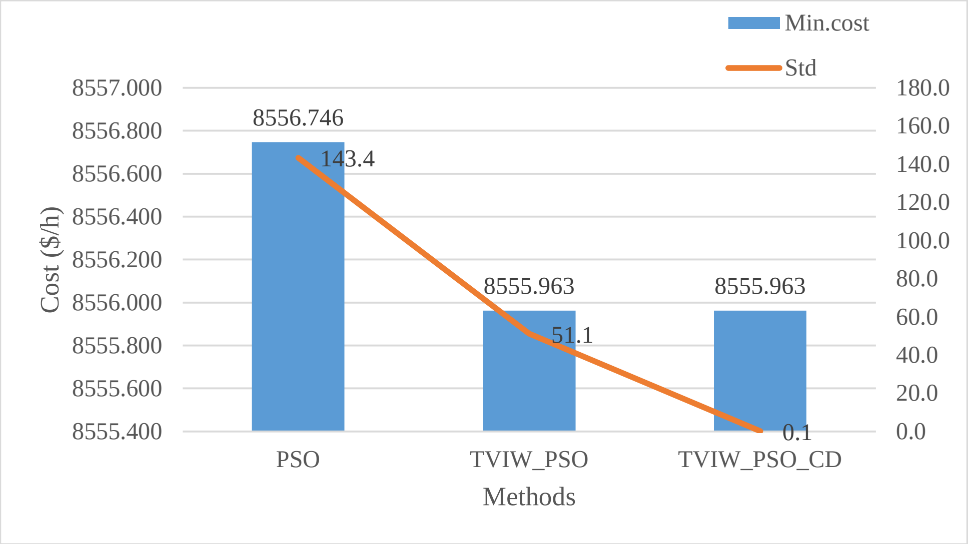

Fig. 3 The Min.cost and Std obtained by three methods in Case 2.

The Figure 3 proves the high performance of TVIW_PSO_CD method comparing with two others. The blue bar of TVIW_PSO method can view that it equal the one belonging TVIW_PSO_CD method but this method is higher than the TVIW_PSO_CD method in term of the Std. Specifically, the Std of TVIW_PSO method is 51.1 whist the similar one of TVIW_PSO_CD method is only 0.1. Therefore the TVIW_PSO method is less stable than the TVIW_PSO_CD method. When comparing with the original PSO method, the TVIW_PSO_CD method is completely better in term of both the Min.cost and the Std. While placing all three methods applied in this case in a larger reference of many other optimal methods presented in Table 4 the results given by TVIW_PSO_CD is better than MADS-LHS [14] and MADS-PSO [14]. The value of Min.cost reported by the other remaining methods in Table 4 are slightly better than the one reached by the TVIW_PSO_CD. However, the differences are not noticeably. On the other hand, although the Min.cost obtained by PSO is better than the MADS-LHS [14] and MADS-PSO [14], but this method still proves its low efficiency among the other methods.

Table 4: The comparison with the other methods in Case 2

Method	**Min. cost ($/h)**	**Method**	**Min. cost ($/h)**
MADS-LHS [14]	8622.0748	LWPSO-CD [19]	8555.9625
MADS-PSO [14]	8629.4156	GCPSO [19]	8555.9625
MADS-DACE [14]	8555.9625	GCPSO-CD [19]	8555.9625
LR-SSMU-CSS [17]	8555.9625	GWPSO [19]	8555.9625
LR-SSMU- SSBS [17]	8555.9625	GWPSO-CD [19]	8555.9625
LCPSO [19]	8555.9625	PSO	8556.746
LCPSO-CD [19]	8555.9625	TVIW_PSO	8555.963
LWPSO [19]	8555.9626	TVIW_PSO_CD	8555.963

4.3 Case 3

In this case, three methods are applied to solve the CHPED problem with power demand of 225 MW and heat demand of 125 MWth. Table 5 indicates the absolute superiority of TVIW_PSO_CD method while comparing with the other methods. In this case, all results in term of Min.cost, Mean.cost and Max.cost obtained by TVIW_PSO_CD are the same, specifically 10074.4875 ($/h) and the Std of TVIW_PSO_CD in this case is zero. This Std is the highly impressive for a meta-heuristic method. On the other hand, the advantage of the TVIW_PSO_CD method is also maintained over the TVIW_PSO method and the original PSO method. The evidence is that the optimal results obtained by TVIW_PSO_CD method are less almost less than the other methods. The evaluation of the Mean.cost, the Max.cost value and the Std given by three methods points out a clear difference regarding the performance of each method. While the Mean.cost of TVIW_PSO_CD method is only 10074.4875 $/h the similar numbers reached by TVIW_PSO method and the original PSO method are 10075.5687 $/h and 10098.6295 $/h, respectively. By making a simple subtract, the Mean.cost of TVIW_PSO_CD method is less than the number obtained by TVIW_PSO method 0.081 $/h and it is also less than the number reached by the original method 24.142 $/h. These numbers are equal the percentage of improvement 0.0008% and 0.24%. Keep doing the same thing with the Max.cost, we get the saving cost over the TVIW_PSO method and the original PSO method are 54.061 $/h and 598.25 $/h, respectively. The improvement percentages in term of Max.cost of TVIW_PSO_CD method in this case while compared with TVIW_PSO method and the original method are 0.53% and 5.61%. The Figure 4 below presents a better look about the outstanding performance of TVIW_PSO_CD method over TVIW_PSO method and the original PSO method.

Table 5: The results obtained in case 3

Method	**PSO**	**TVIW_PSO**	**TVIW_PSO_CD**
Min.cost	10074.4889	10074.4875	10074.4875
Mean.cost	10098.6295	10075.5687	10074.4875
Max.cost	10672.7375	10128.5492	10074.4875
Std	118.38	7.65	0.00

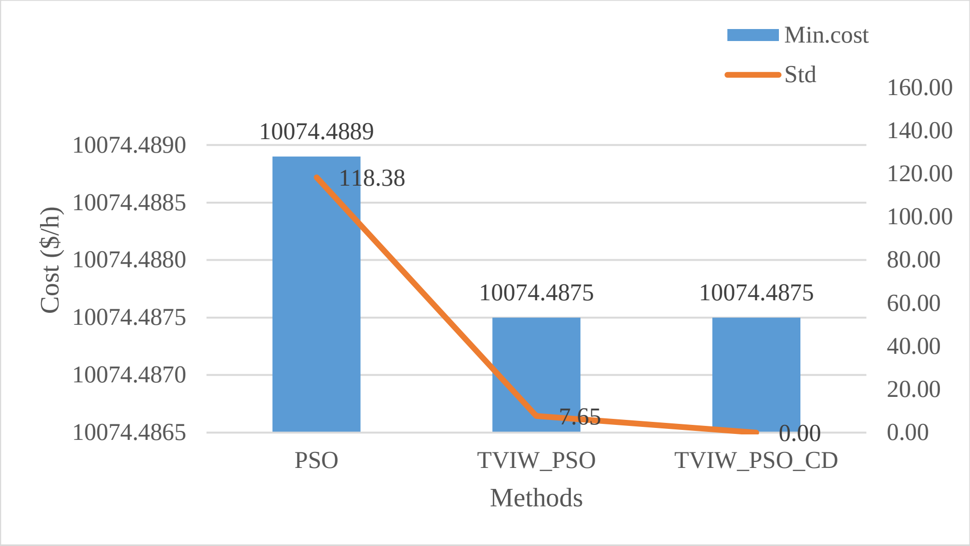

Fig. 4 The Min.cost and Std obtained by three methods in Case 3.

Table 6: The comparison with the other methods in case 3

Method	**Min. cost ($/h)**	**Method**	**Min. cost ($/h)**
MADS-LHS [14]	10101.4753	LWPSO-CD [19]	10074.4875
MADS-PSO [14]	10101.8942	GCPSO [19]	10074.4875
MADS-DACE [14]	10074.4875	GCPSO-CD9 [19]	10074.4875
LR-SSMU-CSS [17]	10074.49	GWPSO [19]	10074.4875
LR-SSMU- SSBS [17]	10074.49	GWPSO-CD [19]	10074.4875
LCPSO [19]	10074.4875	PSO	10074.4889
LCPSO-CD [19]	10074.4875	TVIW_PSO	10074.4875
LWPSO [19]	10074.4875	TVIW_PSO_CD	10074.4875

The Min.cost presented in Table 6 shows that the performance of the TVIW_PSO_CD still very impressive because the Min.cost value obtained in this case by TVIW_PSO_CD is not only equal to most similar ones reported by the other methods but also better than some other methods. Specifically, the Min.cost value given by TVIW_PSO_CD is 10074,485 ($/h) while the Min.cost value reported by MADS-LHS [14], MADS-PSO [14], LR-SSMU-CSS [17] and LR-SSMU-SSBS [17] are respectively 10101.4753 ($/h), 10101.8942 ($/h), 10074.49 ($/h) and 10074.49 ($/h). In addition, PSO is still the lowest effective method among three methods applied in this study.

4. Conclusions

This study successfully applied the new versions of the original PSO for solving the CHPED problem. According to the results given by three methods, the TVIW_PSO_CD proves its outstanding performance while comparing with the original PSO over all aspects such as the minimum cost value, the mean cost value, the maximum cost value and the Std value. In addition, the presence of the Cauchy coefficient in TVIW_PSO_CD is much more effective than the TVIW_PSO, especially in term of the Std value. This claim is demonstrated in all case studies considered in section IV. The standard deviation given by TVIW_PSO_CD is approximately close to zero while the similar one reported by the TVIW_PSO is completely higher and of course the Std value given by the original PSO is also substantially higher than both TVIW_PSO and TVIW_PSO_CD. That means, the TVIW_PSO_CD is truly the most stable method among three method applied in this paper. Besides, the optimal results reached by the TVIW_PSO_CD is also better than many other methods proposed by previous studies.

Appendix

Appendixes, if needed, appear before the acknowledgment.

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