Technological Applied Sciences
ISSN: 1308 7223 (NWSATAS)
ID: 2018.13.3.2A0155

Status : Original Study
Received: December 2017
Accepted: July 2018

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DOI	http://dx.doi.org/10.12739/NWSA.2018.13.3.2A0155	
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SOLUTION OF ECONOMIC DISPATCH PROBLEM WITH THE VALVE-POINT LOAD EFFECT BY META-HEURISTIC ALGORITHMS

ABSTRACT

Economic dispatch problem (EDP) is a balance problem between the minimum fuel cost and demanded power within the active power limits. In this study, economic dispatch problem was implemented by the Particle Swarm Optimization (PSO), Artificial Bee Colony (ABC), Teaching Learning Based Optimization (TLBO) and Gravitational Search Algorithm (GSA) on the power systems of 850 MW including 3 active bus with valve-point load effect, 1800 MW including 13 active bus with valve-point load effect to solve the optimum fuel cost and run time for a comparison. Minimum fuel cost in 3 active bus power system was calculated as 8234.086 $/h in 3.28 s by the TLBO method. In 13 active bus power system, it is calculated as 18019.15 $/h in 8.95 s by the PSO method.

Keywords: Economic Dispatch Problem, Valve-Point Load Effect, Power Systems, Optimization Algorithms

1. INTRODUCTION

In recent years, electric energy has begun to be obtained from many various sources [1]. Each of these energy sources also has its own generation characteristics and energy costs [2]. Saving is a critical issue in electrical power systems, which are basically covered in three parts as production, transmission and distribution. In order to save in the production phase, it is necessary to know how much electricity will be generated by the power plant, so the generation quantity should be determined very well. Power systems have a dynamic and variable structure. Power flow analysis is becoming more important especially for countries where power capacity and energy diversity have increased rapidly like Turkey [3]. If the power flow analysis is not performed or is not efficient enough, the frequency of the electric energy will increase or decrease, causing excessive energy consumption or deterioration of the quality of the energy [4 and 5]. When the power system is thought to be a periodic system due to the generation structure of the electric energy, an attempt is made to design analysis techniques that can transmit power values to generation units both optimally and quickly [6 and 7]. Expansion and diversification of power systems also necessitate the use of advanced calculation methods. These calculation methods, which are different from classical calculation methods, are called meta-heuristic methods. Some of these methods that try to predict future events and are often

How to Cite:
Tefek, F.M., Güçyetmez, M., and Uğuz, H., (2018). Solution of Economic Dispatch Problem with The Valve-Point Load Effect By Meta-Heuristic Algorithms, **Technological Applied Sciences (NWSATAS)**, 13(3): 253-263. DOI:10.12739/NWSA.2018.13.3.2A0155.

inspired by physical or natural phenomena are Particle Swarm Optimization (PSO) [8], Artificial Bee Colony Algorithm (ABC) [9], Gravitational Search Algorithm (GSA) [10], and Teaching-Learning Based Optimization Algorithm (TLBO) [11]. In addition to studies on power flow analysis using these methods, studies involving the effect of valve points on generator boundaries are also made [12 and 13]. In this study, the valve-point load effect is added to the meta-heuristic algorithms which are used effectively in the power flow analysis and applied to IEEE 3 and 13 bus power test systems. Thus, the efficiency of the power systems under the valve-point load effect was compared in terms of fuel cost.

2. RESEARCH SIGNIFICANCE

This study is the first to use four different meta-heuristic methods in the analysis of economic load dispatch altogether. In order to increase the efficiency of large scale power systems, it is necessary to analyze the basic test power systems. In power systems, valve-point load effect can cause ripples or sinusoidal fluctuations in fuel cost problem. This also makes the fuel cost calculation a difficult non-convex problem [14 and 16]. Therefore, a quick and effective solution of the valve-point load effect economic dispatch problem is important. In this study, PSO, ABC, GSA and TLBO algorithms, which are the meta-heuristic techniques for solving the valve-point load effect economic dispatch problem (EDP) which is difficult to find optimal solution, have been applied to 3 and 13 bus power systems for time efficiency and fuel cost comparison. At the same time, this study is important to apply different meta-heuristic methods algorithms in the EDP solution with the valve-point load effect.

3. EXPERIMENTAL METHOD

This section consists of two parts, valve-point load effect economic dispatch problem formulation and optimization algorithms.

3.1. Formulation of Economic Dispatch Problem with Valve-Point Load Effect

Economic dispatch problem (EDP) is known to be able to meet demand by the units of production in the form of a minimum of fuel cost under constraints of the power system [16 and 21]. EDP is a nonlinear problem with equality and inequality constraints [17 and 19]. To more efficiently and consistently calculate the minimum fuel cost, which is the objective function in the EDP, the valve-point load effect is included in the system [12, 15 and 18]. Adding the valve-point load effect to the fuel cost of the generation unit is a more suitable way to realize the real fuel cost calculation. Economic power dispatch problem is a problem that has a non-convex characteristic and is difficult to find an optimal solution [15 and 16]. In Figure 1, the curve drawn with a dark line indicates the fuel cost curve with the valve-point load effect. As shown by the dark lines in Figure 1, the fuel cost function includes nonlinear sinusoidal additions as valve-point fluctuations.

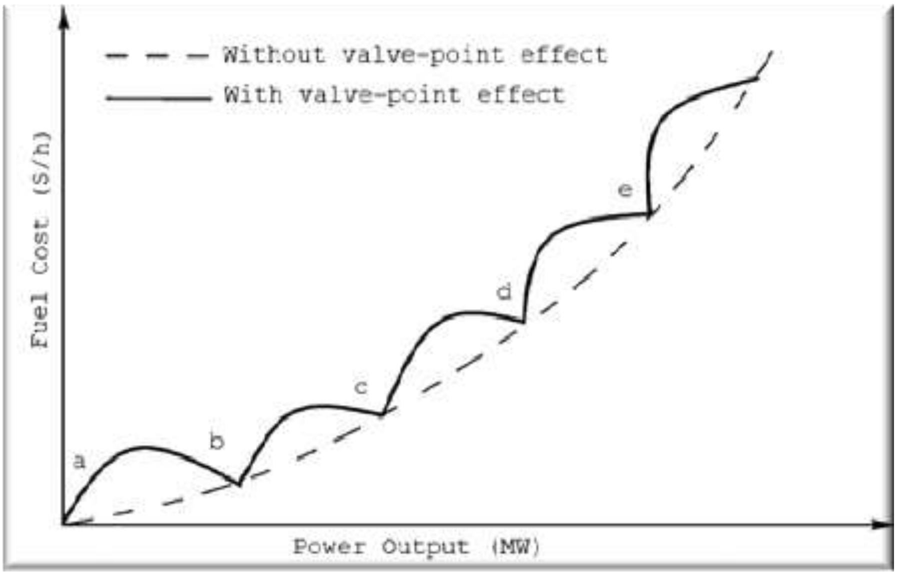

Figure 1. Input-output characteristics of the generation unit with valve-point load effect

Valve-point load effect makes sinusoidal fluctuations as in Equation 1 in the system. This causes the problem to be non-convex and the solution becomes more difficult. Therefore, it is important to make a solution by using optimization algorithms in terms of less calculation time. The formulas and restrictions of the valve-point load effect system are given below.

$$\min F(x) = \sum_{i=1}^{N_G} (a_i P_i^2 + b_i P_i + c_i) + \left| e_i \sin\left(f_i\left(P_i^{min} - P_i\right)\right)\right| \quad (\$/h) \tag{1}$$

$$\sum_{i=1}^{N_G} P_i - P_D - P_L = 0 \tag{2}$$

$$P_L = \sum_{i=1}^{N_G} \sum_{j=1}^{N_G} P_i B_{ij} P_j + \sum_{i=1}^{N_G} P_i B_{0i} + B_{00} \tag{3}$$

$$P_i^{min} \leq P_i \leq P_i^{max} \qquad 1 \leq i \leq N_G \tag{4}$$

In equation 1, F is the fuel cost function of the power system, N_G is generator bus number, P_i is the generation output of the active generating bus i, and a_i, b_i, c_i are the cost fuel coefficients of generating bus i. e_i and f_i are ith generator unit cost coefficients representing valve-point load effect. Equation 2 gives equality constraints between the total power of the system and the total system loads P_D and losses P_L. In equation 3, the loss P_L is calculated by the B_{ij}, B_{0i} and B_{00} loss coefficients. In equation 4, the lower limit (P_i^{min}) and the upper limit (P_i^{max}) inequality constraints of each active power are given. By calculating the equations and inequalities with the optimization algorithms in this way, it is aimed to find the minimum fuel cost with valve-point load effect.

3.2. Power Systems

In this study Case I and Case II cases were established for the demanded power values for the 3-bus power system and the 13-bus power system. In this way, the most optimal fuel cost is calculated for the EDP.

3.2.1. Case I: 3 Bus Power System

This system includes 3 generator bus in a 6-bus system. In Table 1, power limits and cost coefficients of the generator units of the power system are given [14 and 21].

Table 1. Units data for test case I (three-unit case) with valve-point loading. a b, c, e, and f are cost coefficients in the fuel cost function

Bus	P_{min} (MW)	P_{max} (MW)	a	b	c	e	f
P1	100	600	0.001562	7.92	561	300	0.0315
P2	50	200	0.00482	7.97	78	150	0.063
P3	100	400	0.00194	7.85	310	200	0.042

3.2.2. Case II: 13 Bus Power System

The power limits and cost coefficients of the 13 bus test system in generator bus are given in Table 2 [14].

Table 2. Case 2: Units data for test case II (13-unit case) with valve-point loading. a, b, c, e, and f are cost coefficients in the fuel cost function

Bus	P_{min} (MW)	P_{max} (MW)	a	b	c	e	f
P1	00	680	0.00028	8.10	550	300	0.035
P2	00	360	0.00056	8.10	309	200	0.042
P3	00	360	0.00056	8.10	307	200	0.042
P4	60	180	0.00324	7.74	240	150	0.063
P5	60	180	0.00324	7.74	240	150	0.063
P6	60	180	0.00324	7.74	240	150	0.063
P7	60	180	0.00324	7.74	240	150	0.063
P8	60	180	0.00324	7.74	240	150	0.063
P9	60	180	0.00324	7.74	240	150	0.063
P10	40	120	0.00284	8.6	126	100	0.084
P11	40	120	0.00284	8.6	126	100	0.084
P12	55	120	0.00284	8.6	126	100	0.084
P13	55	120	0.00284	8.6	126	100	0.084

3.3. Algorithms

3.3.1. PSO

The Particle Swarm Optimization (PSO) algorithm is a population-based optimization technique inspired by the search for food for living creatures such as birds and fish moving in flocks in nature [8]. The algorithm starts with a random bird search in the search space of a group of birds. Through communication with other birds, it aims to reach the food that is the global outcome by approaching to find food in each iteration. In power systems, the algorithm is run under the necessary equations and constraints to minimize the fuel cost, which is the objective function. The application of the PSO algorithm in the EDP with valve-point load effect is given below.

The pseudo code of PSO algorithm is given in the following:

```
Set parameters
Create Initial Population
REPEAT {
      FOR  {Each particle
            Calculate Objective Function Values
            Find the Best Local Value
           }
      END FOR
Find the Best Global Value
      FOR  {Each particle
            Update the Velocity Vector
            Update the Position Vector
            Calculate Objective Function Values
```

```
            Update the Best Local Value
            Update the Best Global Value
            }
      END FOR
} UNTIL (The termination criterion is met)
```

3.3.2. ABC

The Artificial Bee Colony Algorithm was inspired by the problem of solving the bee colony in nature to solve the problem of finding flower pollen in order to be able to make honey and to feed and to find other bees by creating certain rings towards the Sun[9]. The application of the ABC algorithm in the EDP with valve-point load effect is given below. The pseudo code of ABC algorithm is given in the following:

```
Set parameters
Assign the Initial Values
Calculate the fitness values
REPEAT {
Send the employee bees to the nutrition sources
      FOR {
            Calculate the nectar amount
            Calculate the probability values in the selection of
            observer bees Select the food source area based on the
            calculated probability values of the observer bears
            Termination from the Source: Limit and explorer bee
            production
          }
      END FOR
Keep the best solution in memory.
} UNTIL (The termination criterion is met)
```

3.3.3. GSA

It is Newton's movement and a physics-based meta-heuristic optimization algorithm that is inspired by gravity laws. It is developed by Rashedi et al. (2009) [10] Each particle in the search space is considered as a mass in the Gravitational Search Algorithm (GSA). For this reason, it is possible to define the GSA as an artificial mass system [10]. The greatest mass is the closest to the result and attracts others. The following is the application of the GSA algorithm in the EDP with valve-point load effect. The pseudo code of GSA algorithm is given in the following:

```
Set parameters
Assign Initial Values
Randomly position N members for initial population
REPEAT {
      FOR {
            Calculate the fitness value for each mass
            Calculate mass, force, acceleration values respectively
            Perform speed and location update
          }
      END FOR
Update best, worst eligibility values
} UNTIL (The termination criterion is met)
```

3.3.4. TLBO

TLBO is a socially based optimization method inspired by the roles of teachers and students in a class. In this algorithm, students are divided into classes and it is assumed that the best learners in a class can learn as much as teachers. In this way, the best result is achieved by the information exchange among the students themselves and the exchange of information with the teachers by the students [11]. The application of the TLBO algorithm in the EDP with valve-point load effect is given below. The pseudo code of TLBO algorithm is given in the following:

```
Set parameters
Assign Initial Values
Randomize students for initial population
REPEAT {
      FOR { Each teacher
            Calculate objective function
            Choose the most suitable teacher for your students
          }
      END FOR
      FOR { Each student
            Identify the best learners based on interacting with each
            other
          }
      END FOR
Update best result
} UNTIL (The termination criterion is satisfied)
```

3.3.5. Algorithm Parameters

Algorithm parameters used in this study are given in Table 3. Each algorithm is run 30 times using the parameters in Table 3 to find the minimum fuel cost, which is the objective function in EDP. The parameter values in Table 3 have been chosen because they are frequently used values in the literature [8 and 11]. All experimental runs were performed using the i7-6700HQ 2.6 Ghz processor, 8 GB memory (RAM), the Windows 10 operating system, and the MATLAB R-2015b program.

Table 3. Initial algorithm parameters for the GSA, TLBO, PSO, and ABC

Algorithm	Parameter	Value
GSA [10]	Population (Mass) number	50
	G_0	20
	α	100
	Number of Iterations	100
TLBO [11]	Population number	50
	Number of Classes	25
	Number of Iterations	100
ABC [9]	Colony Size Number	50
	Food Number	25
	Onlooker Number	25
	Employed Bee Number	25
	Limit	100
	Number of Iterations	100
PSO [8]	Population number	50
	Inertia Weight (w)	1
	Inertia Weight Damping Ratio (wdamp)	0.99
	Personal Learning Coefficient (c1)	1.5
	Global Learning Coefficient (c2)	2.0
	Number of Iterations	100

4. COMPUTATIONAL RESULTS

The minimum fuel cost results calculated by the ABC, GSA, PSO and TLBO algorithms run 30 times in the valve-point load effect EDP solution are taken and compared. For Case I in Table 4; The TLBO algorithm between the algorithms for the 3-bus system calculates both the lower fuel cost and the shorter run time than the others.

Table 4. Case I: 3-bus power system results for demanded 850 MW power

Bus No. (MW)	PSO	ABC	GSA	TLBO
P1	498.9348	497.3909	496.0515	300.2651
P2	99.8777	100.9	108.6919	149.7356
P3	251.1875	252.7908	247.946	400
Fcost ($/h)	8241.192	8287.442	8371.18	**8234.08**
Time (s)	3.601797	3.58248	4.57913	**3.28183**

Table 5 compares the results of the ABC, GSA, PSO and TLBO algorithms and other studies in the literature [14]. According to Table 5, it is seen that the meta-heuristic methods applied in this study are better than other studies in the literature in terms of time efficiency. TLBO calculated the fuel cost with 8234.08 ($/h) at the best run time in terms of time efficiency within all algorithms. The IFEP [14] algorithm found the best fuel cost with a statistical difference of 0.00001244. This shows that the TLBO algorithm finds close results with the literature in valve-point load effect EDP analysis of the 3-bus power systems.

Table 5. Comparison of the results of the 3-bus power system for valve-point load effect EDP with the literature

Algorithms	Time (s)	Fcost ($/h)
PSO	3.601797	8241.192
ABC	3.58248	8287.442
GSA	4.57913	8371.18
TLBO	**3.28183**	8234.08
GAB[14]	32.46	8234.08
MFEP[14]	6.31	8234.08
IFEP[14]	6.11	**8234.07**

As seen in Figure 2, the PSO algorithm and TLBO algorithms converge faster than the others. The ABC and GSA algorithms for the 3-bus power system were found to be higher than others in terms of fuel cost. From the Figure 2, it can be seen that the initial fuel cost value of the ABC and GSA algorithms is higher than the other algorithms. At the same time, it is observed that the ABC algorithm at 30th iteration and the GSA algorithm after 10th iteration are snagged with the local minimum solutions for the valve-point load effect EDP solution in 3-bus power system. In Figure 2, between 50 and 100 iterations are shown for a better understanding of the fuel cost ($/h) graph.

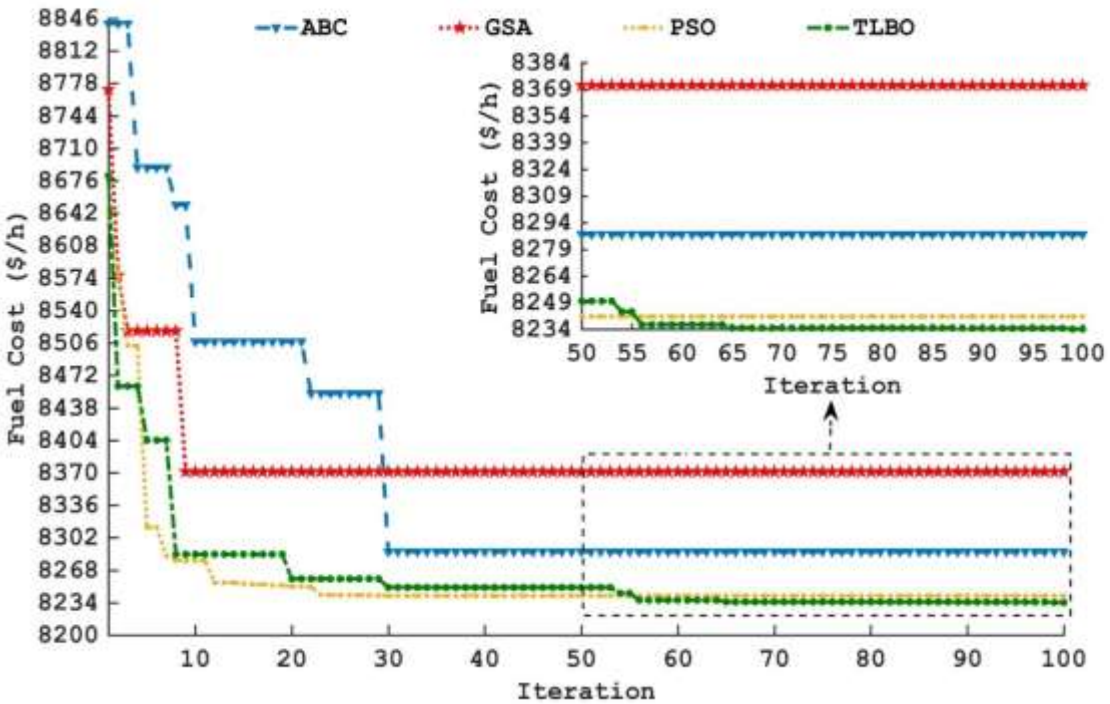

Figure 2. Case 1: ABC, GSA, PSO and TLBO algorithms convergence curves for minimum fuel cost of the 3 bus power system with valve-point load effect

For Case II in Table 6: The PSO algorithm found fuel cost lower than other algorithms for the valve-point load effect EDP problem. From a time, perspective, the PSO algorithm was found to be faster than the others.

Table 6. Case II: 13-bus power system results for demanded 1800MW power

Bus (MW)	PSO	ABC	GSA	TLBO
P1	538.5954	618.9297	358.7724	538.515
P2	149.7884	360	224.4451	360
P3	149.9829	73.4662	224.4158	360
P4	109.8856	60	109.874	60
P5	109.8751	64.58271	109.0367	60
P6	109.9143	96.72469	109.4754	60
P7	109.881	106.6898	109.45	60
P8	109.8761	60	109.753	60
P9	109.9035	108.8761	109.5935	60
P10	77.42342	73.23478	76.61977	40
P11	77.42572	41.40857	76.40058	40
P12	55.00001	55	92.5689	55
P13	92.4495	84.782830	90.54056	55
Fcost ($/h)	**18019.15**	18559.78	18090.11	18269.3
Time (s)	**8.952944**	9.422345	10.788432	9.66988

Table 7 compares the results of the ABC, GSA, PSO and TLBO algorithms with other studies in the literature [14]. In Table 7, PSO, ABC, GSA and TLBO algorithms calculated the fuel cost in a shorter time than other studies for time efficiency. In the analysis of power systems, the cost of fuel is negatively impacted in every second of the calculation. Hence, the superiority of the meta-heuristic algorithms can be seen in terms of time. In this study, PSO found better fuel cost than other meta-heuristic methods in a shorter period, from intuitive methods that investigated efficiency and feasibility. In the literature, the IFEP [14] algorithm yielded the lowest fuel cost at 17994.07 ($ / h). There is statistically 0.0001391 difference ratio between IFEP [14] and PSO algorithm. This shows the feasibility of the PSO algorithm for the EDP solution in terms of time efficiency.

Table 7. Comparison of the results of the 13-bus power system for valve-point load effect EDP with the literature

Algorithms	Time (s)	Fcost ($/h)
PSO	**8.952944**	18019.15
ABC	9.422345	18559.78
GSA	10.78843	18090.11
TLBO	9.66988	18269.3
CEP[14]	293.41	18048.21
MFEP[14]	315.98	18028.09
IFEP[14]	156.81	**17994.07**

From Figure 3, it can be said that the convergence curve of the PSO algorithm calculates for a lower number of iterations and a more efficient fuel cost than the others. From the Figure 3, it is seen that the initial fuel cost of the PSO algorithm is lower than other meta-heuristic algorithms. This shows that the 13-bus power system is not snagged to the local minimum from the beginning of the PSO algorithm for the valve-point load effect EDP solution. In Figure 3, between 50 and 100 iterations have been shown to converge earlier than others in the PSO algorithm.

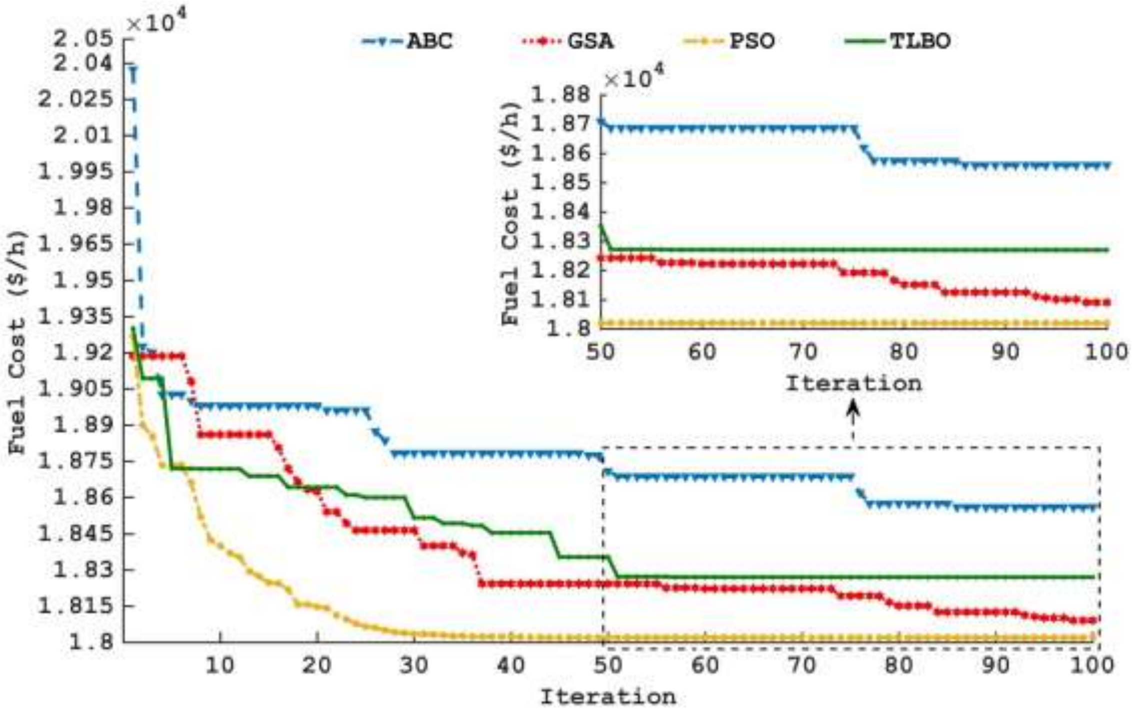

Figure 3. Case II: ABC, GSA, PSO and TLBO algorithms convergence curves for minimum fuel cost of the 13-bus power system with valve-point load effect

5. CONCLUSION AND RECOMMENDATIONS

In power systems, the optimal minimum computation due to sinusoidal fluctuations is a difficult and non-convex problem. In this study, ABC, GSA, PSO, and TLBO meta-heuristic methods in 3 and 13-bus power systems were applied to solve the economic dispatch problem with valve-point load effect. Meta-heuristic methods are used to minimize the fuel cost, which is the objective function, as well as run time analysis. Due to the instantaneous change in power demand in power systems, time efficiency is important for the system operation to meet this demand. It is seen that the EDP solution with the used meta-heuristic method is very close to the literature, but it has crucial time efficiency and has shorter run time than the other studies. At the same time; the analysis includes both the fuel cost and the analysis period. From the analysis results, it is seen that the PSO optimization method is more efficient as the power system capacity increases. For larger scale power systems from the analysis results, it can be concluded that the PSO optimization technique will be suitable both in terms of fuel cost and analysis time.

NOTICE

This study was presented as an oral presentation at the I. International Scientific and Vocational Studies Congress (BILMES 2017) in Nevşehir/Ürgüp between 5-8 October 2017.

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