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MULTI-OBJECTIVE COMBINED ECONOMIC AND EMISSION DISPATCH BY FULLY INFORMED PARTICLE SWARM OPTIMIZATION

Muhammad F. Tahir,[*] Kashif Mehmood,[**,***] Chen Haoyong,[*] Atif Iqbal,[****]
Adeel Saleem,[***] and Shaheer Shaheen[*****]

Abstract

Combined economic and emission dispatch problem (CEEDP) leads towards economical and greener power system by improving the economy (reducing fuel costs) and minimizing emission (reducing greenhouse gases) while fulfilling power demands. In this work, a fully informed particle swarm optimization (FIPSO) is proposed to optimize CEEDP that is considered a multi-objective optimization problem. Higher accuracy in case of heavily constrained optimization in comparison to simple PSO makes FIPSO even more useful while addressing CEEDP. This research does not focus only to solve CEEDP by FIPSO algorithm but also to compare it with PSO and is tested on IEEE 30 bus benchmark system with six generators and 20 load buses. In addition, ED problem with three-generator system is solved by including valve-point loading effect, and its comparison with other popular algorithms is made. Optimizing accuracy, fast convergence, less computational time and fewer emission values by the proposed algorithm show its superiority in comparison to other conventional methods.

Key Words

Combined economic emission dispatch problem, economic dispatch, fully inform particle, price penalty factor, swarm optimization, valve-point loading effect

1. Introduction

Rapid growth in electricity demand due to industrialization and urbanization is mostly met by fossil fuel sources such as coal, oil and gas [1]–[2]. Abundunt use of fossil fuel sources increase electricity tariff and disrupt the ecological system [3]–[6]. Though trend is shifting towards renewable integration but most of the energy demands are yet fulfilled by thermal power plants. Recently, many studies have been carried out to enhance the electric power transmission capabiliy or look for alternatives to reduce energy production cost of thermal power plants that paves theroad for economic dispatch (ED) [7]–[11].

ED calculates the least number of generating units required to produce desire power (unit commitment) and power produced from each generating unit (unit dispatch) [10]. Characteristics of all generating units, efficient on-off scheduling of generators are required to operate and dispatch the unit economically [12]. Therefore, generator scheduling with specified fuel or water supplies is integrated in EMSs. However, other than reducing the cost, greenhouse gas reduction is equally important to get one step closer towards clean environment. Consequently, combined economic and emission dispatch problem (CEEPD) has become prominent that focuses on minimizing not only fuel cost but also emissions level [13]–[14].

1.1 Economic Dispatch

For ED, several solutions are deduced, which are classical and advanced that include priority list, lambda iteration [15], linear programming [16], quadratic programming [17], Lagrangian relaxation [18], gradient and Gauss–Seidel [19] methods. Traditional schemes effectively solve ED problems when generating units' fuel-cost curves are piece-wise linear but becomes non-convex optimization in case of non-linear and non-smooth characteristics of generating units. Therefore, to solve such problems efficiently, advanced methods are gaining popularity.

[*] School of Electric Power, South China University of Technology, Guangzhou, China; e-mail: epfaizantahir_2k7@mail.scut.edu.cn, eehychen@scut.edu.cn
[**] School of Electrical Engineering, Southeast University, Nanjing, China; e-mail: kashifzealot@gmail.com
[***] IeCE Laboratory, Department of Mechanical Engineering, The University of Lahore, Lahore, Pakistan; e-mail: metadeelsaleem@gmail.com
[****] School of Electrical & Electronic Engineering, North China Electric Power University, Beijing, China; e-mail: atifiqbal-688@yahoo.com
[*****] Sui Northern Gas Pipelines Limited, Government of Pakistan, Pakistan; e-mail: shaheershaheen16@gmail.com
Corresponding author: Kashif Mehmood

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Advanced methods such as genetic, ABC and PSO requires a lot of time, faces contradiction in exploration and exploitation and easily falls into local optimum respectively. Observing the merits and demerits of all the above techniques, PSO is mostly preferred due to fast convergence rate, better accuracy, less computational time and robustness. However, our research is not limited to ED; it covers both aspects of the economy and emission, and till date following research studies have been done to solve CEEDP.

1.2 Combine Economic and Emission Dispatch

In [20], the authors uses a gravitational search algorithm to solve CEEDP. Though this algorithm is not so mature, it is showing rapid growth in optimization problems over the last few years. Moreover, computational time and inability to converge in case of failure of generating the initial population make it less attractive to solve ED issue in comparison to already matured algorithms. Flower pollination algorithm (FPA) is deployed in [21] to address CEEDP for six different cases by considering the valve-point loading effect that indicates the robustness of FPA. However, like any other metaheuristic method, this algorithm also suffers from global and local exploitation balance during the search process. CEEDP by using adaptive wind-driven optimization (AWDO) is performed on IEEE 30 bus system which is discussed in [22]. Though results indicate the accurate and effective solution for the given problem but proper selection of optimum coefficients, parameter combinations, boundary values and optimum location makes it complicated and not easy to use.

Finally, PSO is exploited in [23] for solving CEEDP. PSO algorithm is deduced from group behaviour but it is not necessary that every individual is influenced by neighbour best behaviour. Therefore, for faster convergence with least computational effort, it is better that every individual is fully informed which can be done by Fully Informed Particle Swarm Optimization (FIPSO).

Multi-objective problem is generally solved by two approaches: i) Pareto front optimality that faces the problem of reducing the size of set. ii) Aggregation of all objective functions into a single composite objective function. We applied the second approach in this research to avoid any complexity by using FIPSO which simultaneously optimizes the multi-objectives as indicated in (1) and results in single optimal solution.

Main contributions of this paper are: (1) Load flow analysis has been done to find the loss coefficient matrix. (2) FIPSO has been used for the first time to solve CEEDP on IEEE 30 bus system, and comparison of cost and emission functions is made with PSO. (3) Finally, FIPSO is employed to solve ED problem with three-generator system by taking into account the valve-point loading effect. The cost function comparison is made with other state-of-the-art algorithms such as genetic algorithm, evolutionary programming, improved evolutionary programming, modified particle swarm optimization and Particle Swarm Optimization with recombination and dynamic linkage discovery algorithms.

Rest of the paper is organized as follows: Section 2 discusses problem formulation while Section 3 elaborates methodology and data simulation. Section 4 illustrates case studies and results simulation along with comparisons. Finally, Section 5 reports the concluding remarks.

2. Problem Formulation

ED and emission dispatch are substantially different as ED minimizes the total fuel cost (operating cost) of the system by defying the emission constraint while emission dispatch lessens the total emission of the system by contravening the economic constraints. Consequently, it becomes essential to determine an operating point which attains a balance between total cost and total emission. This can be accomplished by CEEDP which is the multi-objective issue but can be converted into a single optimization problem by establishing price penalty factor (h) as shown in (1).

$$Minimize \qquad \Phi = C_t + {h_i}^* E(\$/hr) \tag{1}$$

The price penalty factor (hi) is defined as the ratio between the maximum fuel $[F(P_{Gi(\max)})]$ cost and maximum emission $[E(P_{Gi(\max)})]$ of the corresponding generator as represented in (2).

$$h_i = \frac{F(P_{Gi(\max)})}{E(P_{Gi(\max)})} \$/lb \tag{2}$$

Φ represents the total operating cost that includes the cost of fuel and implied cost of the emission. The issue converged to simple ED problem, once hi is ascertained. Significant reduction in fuel costs and emission can be achieved by optimal scheduling of generating units.

2.1 Objective Functions

The first objective function (C_t) is to reduce the overall cost.

$$\text{Minimize} \qquad C_t = \sum_{i=1}^{n} C_{G_i} \tag{3}$$

where C_{Gi} is the cost function of i^{th} generator and can be represented by quadratic equation as shown in (4).

$$C_{Gi} = \alpha_i + \beta_i P_{Gi} + \gamma_i P_{Gi}^2 \tag{4}$$

where P_{Gi} is the true or real power generated by i_{th} power generating unit, α_i signifies the total static cost, β_i indicates the semi-fixed cost and γ_i represents the running and operation cost.

The second objective function is to minimize emission dispatch that is modelled by using second-order polynomial functions as represented in (5).

$$\text{Minimize :}$$
$$E = \varphi_i P_{Gi}^2 + \chi_i P_{Gi} + \varepsilon_i + \rho_i * \exp(\xi_i * P_{Gi}) \text{ lb/hr} \tag{5}$$

φ_i, χ_i, ε_i, ρ_i, ξ_i are emission coefficients of the i_{th} generating unit.

Table 1
Cost Coefficient and Generator Data

Gen. unit	α (\$/MW^{2}hr)	β (\$/MWhr)	γ (\$/hr)	P$_{\min}$ (MW)	P$_{\max}$ (MW)
1	0.007	7	240	100	500
2	0.0095	10	200	50	200
3	0.009	8.5	220	80	300
4	0.009	11	200	50	150
5	0.008	10.5	220	50	200
6	0.0075	12	120	50	120

2.2 Constraints

Power loss, load demand and power generation limits are the system constraints represented in (7) that must remain within limits throughout the operation.

$$\sum_{i=1}^{n} P_{Gi} = P_D + P_L \tag{6}$$

In (6) represents that power generated from any generating unit that must satisfy the load demand (P_D) and cover the transmission losses (P_L) all the time. The maximum power generated should be within its maximum.

$P_{Gi(\max)}$ and $P_{Gi(\min)}$ limits are shown in (7).

$$P_{Gi(\min)} \leq P_{Gi} \leq P_{Gi(\max)} \tag{7}$$

3. Methodology and Data Simulation

PSO algorithm habituates neighbours' best result information to modify its position and velocity vectors. However, it is not necessary that the best neighbour has a better region in comparison to the second or third best neighbour at that particular time t. Therefore, FIPSO does not focus only on best neighbour but receives information from all the neighbours. Further, difference between PSO and FIPSO lies in the velocity updating pattern, for kth particle and dth dimension, velocity update equation for FIPSO is illustrated by (8) and (9).

$$v_{k,d} = \chi \left[v_{k,d} + \sum_{n=1}^{k} \frac{U(0,\beta)(pp_{k,d(n)} - p_{k,d})}{K} \right] \tag{8}$$

$$p_{k,d} = p_{k,d} + v_{k,d} \tag{9}$$

where χ is constriction coefficient, K is the number of neighbours which particle k has, $U(0,\beta)$ is the uniformly distributed random numbers between 0 and constant β, $pp_{k,d(n)}$ is the best position acquired so far by an nth neighbour of a particle k.

Constriction coefficient χ is use to avoid the explosion of velocity of a particle and guarantees the convergence. Constriction factor χ is given by (10).

$$\chi = \frac{2}{|2 - \beta - \sqrt{\beta^2 - 4\beta}|} \tag{10}$$

where β is the constant. To guarantee the stability, the β must be greater than 4. As β will increase, χ will be reduced which will lead to slower response. The β=4.1 will be the smallest value to have the fastest response and guarantees stability. Normally, $4.1 \leq \beta \leq 4.2$ leads to better solution.

W depicts swarm size and w signifies the number of control variables, and the proposed swarm size is given by (11).

$$W = 93.67 + 2 \times \sqrt{w} \tag{11}$$

The basic flowchart for PSO and FIPSO is almost the same, but the primary difference lies in updating the pattern of particle position and velocity vectors, which is [24]. In this flowchart, k highlights current particle and z represents the current iteration. The basic parameters needed for simulating FIPSO and its values are almost same as that of basic PSO.

CEEDP is applied to IEEE 30 bus system that has 20 load buses and six generator buses. IEEE 30 bus system generator data that includes coefficients, minimum and maximum power generating capability given in Ref [8]. and Table 1, respectively.

Transmission loss coefficients (Bij) for IEEE 30 bus are also included in problem optimization for the calculation of power loss (12). Bij is obtained from Newton Raphson method represented in (13). The emission data (SOx and NOx Emissions) related to IEEE 30 bus six generators are represented in Table 2.

$$P_L = \sum_{i=1}^{n} \sum_{j=1}^{n} P_{\mathrm{Gi}} B_{\mathrm{ij}} P_{\mathrm{Gj}} + \sum_{i=1}^{n} B_{0i} P_{\mathrm{Gi}} + B_{00} \tag{12}$$

$$B_{ij} = \begin{bmatrix} 1.40 & 1.70 & 1.50 & 1.90 & 2.60 & 2.20 \\ 1.70 & 6.00 & 1.30 & 1.60 & 1.50 & 2.00 \\ 1.50 & 1.30 & 6.50 & 1.70 & 2.40 & 1.90 \\ 1.90 & 1.60 & 1.70 & 7.10 & 3.00 & 2.50 \\ 2.60 & 1.50 & 2.40 & 3.00 & 6.90 & 3.20 \\ 2.20 & 2.00 & 1.90 & 2.50 & 3.20 & 8.50 \end{bmatrix} \tag{13}$$

where, $B_{0i} = [0]$ and $B_{00} = [0]$.

Table 2
Emission Data of Generators

Gen. units	α (lb/MW^{2}h) x1E-6	β (lb/MWh) x1E-4	γ (lb/h) x1E-2	η (lb/h)	δ (1/MW) x1E-2
1	6.49	−5.554	4.091	0.002	2.587
2	5.46	−6.047	2.543	0.005	3.333
3	4.59	−5.094	4.258	1E-6	8.000
4	3.38	−3.550	5.326	0.002	2.000
5	4.59	−5.094	4.258	1E-6	8.000
6	5.15	−5.555	6.131	0.001	6.667

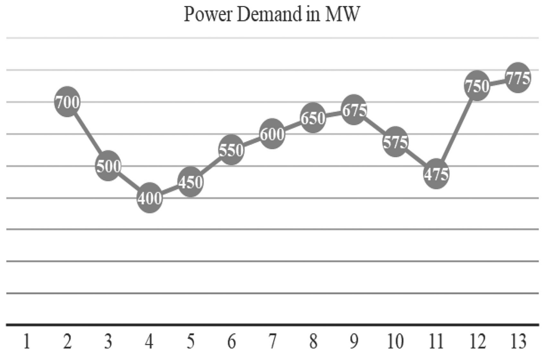


Figure 1. Load curve considered for the case studies.

These emission coefficients are related to the second objective function that needs to minimize. The load curve (MW) of 12 h considered for the different case studies is depicted in Fig. 1.

4. Case Studies and Results Simulations

The research is divided into four case studies that are summarized in Table 3.

4.1 Case 1 Minimization of Cost Functions without Emissions

In Case 1, fuel cost is optimized only as it is a mono-objective function. PSO and FIPSO have been applied for total power generation and cost analysis. Comparison between PSO and FIPSO is highlighted in Fig. 2, respectively, which also signifies the superiority of FIPSO over PSO.

It can be observed that against each hour, a significant reduction in total power generation and fuel cost can be seen in the case of FIPSO when comparing with PSO. Total fuel cost and power generation are reduced from 85,989.3$ to 85,858. 8$ and from 7,197.2MW to 7,184.8MW, respectively.

4.2 Case 2 Minimization of Emission Function without Cost Function

As mentioned in (5), the emission coefficients of the i_{th} generating unit are φ_i, χ_i, ε_i, ρ_i, ξ_i. Figure 3 illustrates the total optimal active power of generating units to optimize the emission objective function considering power transmission losses. The best emission optimized using FIPSO is 6.96 (lb/h) which is lower than that of the PSO algorithm.

4.3 Case 3 Combined Economic and Emission Dispatch (CEED)

The total objective function is the minimization of the cost function and the emission functions. Min (E + C). The result for CEED including penalty factor is shown in Table 4, and total losses using PSO and FIPSO are depicted in Fig. 4.

Not only transmission losses are lessened by using FIPSO, but its convergence rate is also faster in comparison to PSO as portrayed in Fig. 5. The comparison of PSO and FIPSO regarding convergence rate on three-bus system where FIPSO is considerably faster than PSO is shown in Fig. 6.

4.4 ED Comparison with Other Algorithms

In this case, the focus is to solve ED problem with non-smooth functions by taking into consideration the valve-point loading effect. The cost function is acquired that stems from ripple curve for more precise modelling. This curve comprises high-order non-linearity and irregularity because of valve-point effect and must be defined by a sine function. Therefore, (4) can be modified as (14).

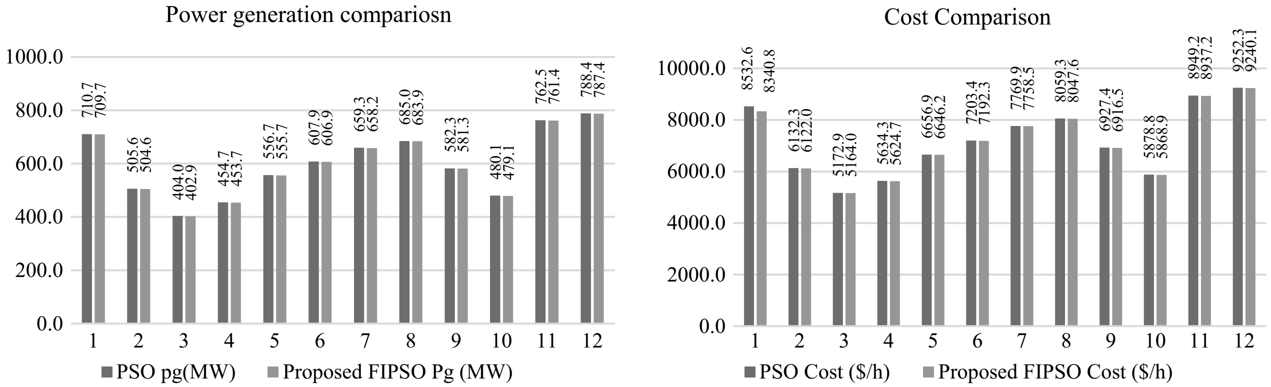
$$\underset{Gi}{\tilde{C}} = C_{Gi} + e_i \sin(f_i(P_{Gi}^{\min} - P_{Gi})) \tag{14}$$

where e_i and f_i are constants of valve-point effect of generators. The three-bus system has been studied for the comparison of proposed algorithm with the previously proposed algorithms. The cost coefficients and generator data are given in Table 5.

FIPSO is used to solve ED problem with three generators, and total demand for the system is 850 MW. The experiments were carried out for 100 independent trials to evaluate the performance of FIPSO on the ED problem with valve-point loading effects. The numerical results for the three-unit system are given in Table 6. ED is a very renowned problem in power systems analysis, and a

Table 3
Summary of Case Studies

Data	Cases	Cost Function Minimization	Emission Function Minimization	Algorithms used
IEEE 30 bus 6 Generator	1	✓	×	PSO, FIPSO
IEEE 30 bus 6 Generator	2	×	✓	PSO, FIPSO
IEEE 30 bus 6 Generator	3	✓	✓	PSO, FIPSO
IEEE 3 bus 3 Generator	4	✓	×	FIPSO and other state of the art algorithms



(a) (b)

Figure 2. (a) Power generation comparison of PSO and FIPSO (b) Cost comparison of PSO and FIPSO.

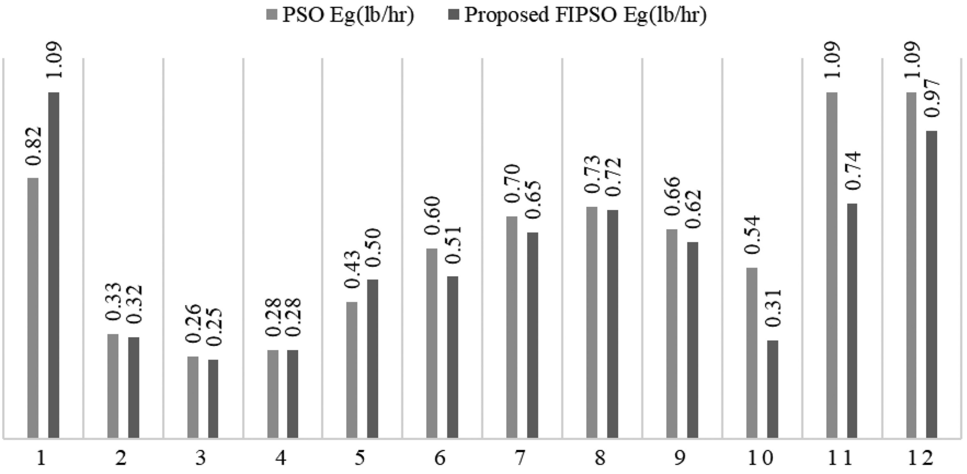


Figure 3. Result for the minimization of emission function.

variety of algorithms have been purported to attain better results. Cost function comparison for ED by using different algorithm references [27]–[29] with FIPSO is portrayed in Table 7. It is considerably evident that FIPSO method acquires splendid results in reducing objective function more in comparisons to the rest of the algorithms.

The time complexity using FIPSO is less than the simple PSO which is analysed by computing the average time in both IEEE 3 and 30 Bus using PSO and FIPSO.

5. Conclusion

In this work, FIPSO algorithm is successfully applied to solve combine economic and emission dispatch issue to minimize fuel cost and emissions in least computational time. The effectiveness of proposed technique is tested on IEEE 30-bus six-generator system, and the multi-objective CEEDP is converted into single objective function by introducing a price penalty factor. Fast convergence, less

Table 4
Combine Economic and Emission Dispatch

Hours	Pd (MW)	PSO-Pg (MW)	FIPSO-Pg (MW)	PSO Cost ($/h)	FIPSO Cost ($/h)	Penalty Factor
1	700	712.2	711.6	9,275.30	9,271.5	793.0
2	500	506.4	505.2	6,541.10	6,507.7	500.1
3	400	404.2	403.1	5,422.00	5,332.4	500.1
4	450	455.4	454.5	5,939.40	5,947.3	500.1
5	550	557.9	558.4	7,255.80	7,187.1	565.1
6	600	608.6	608.5	7,756.30	7,852.8	793.0
7	650	660.5	660.5	8,433.50	8,626.6	793.0
8	675	686.3	685.7	8,947.20	8,889.9	793.0
9	575	584.2	582.8	7,625.70	7,538.4	793.0
10	475	481.1	479.6	6,390.70	6,193.9	500.1
11	750	765.3	763.1	10,308.4	9,810.7	793.0
12	775	790.9	788.9	10,322.6	10,414.5	793.0
Total	7,100	7,213	7,201.9	94,218.0	93,572.8	8,116.5

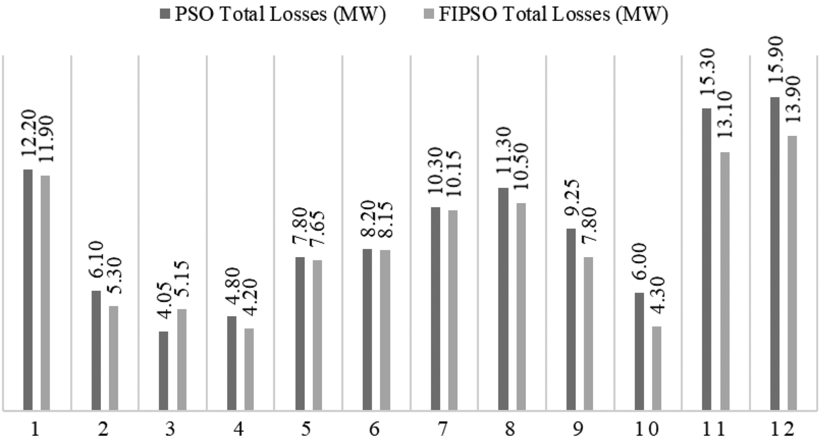


Figure 4. Total transmission losses histogram.

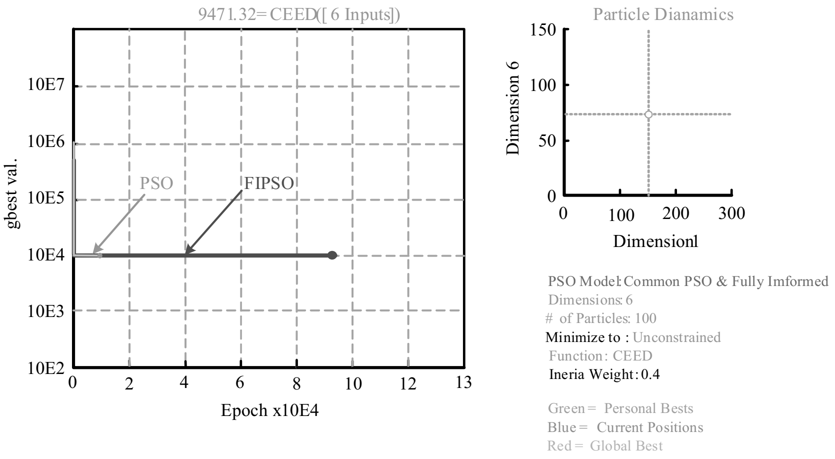


Figure 5. Convergence of PSO and FIPSO for case 3 at PD = 700 MW.

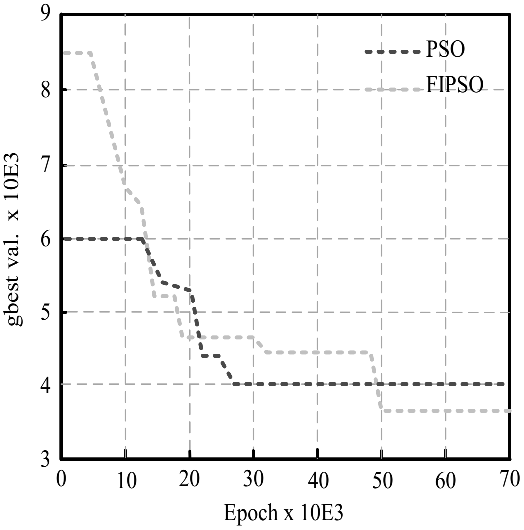


Figure 6. Convergence characteristic of PSO and FIPSO for three-bus system.

Table 5
Cost Coefficients and Generator Data

Gen. Units	$\alpha\ (\$/\mathrm{MW}^2\mathrm{hr})$	$\beta\ (\$/\mathrm{MWhr})$	$\gamma\ (\$/\mathrm{hr})$	$\mathrm{c}\ (\$/\mathrm{hr})$	$\mathrm{f}\ (\$/\mathrm{hr})$	$\mathrm{P}_{\mathrm{min}}$ (MW)	$\mathrm{P}_{\mathrm{max}}$ (MW)
1	0.001562	7.92	561	300	0.0315	100	600
2	0.00482	7.97	78	150	0.063	100	400
3	0.00194	7.85	310	200	0.0142	50	200

Table 6
Cost Function Comparison with Different Algorithms

No.	Researcher	Algorithm	Minimum Cost (\$)
1	D. C. Walters and G. B. Sheble [25]	Genetic Algorithm (GA)	8,237.6
2	Y.-M. Park, J. R. Won [26]	Improved Evolutionary Programming (IEP)	8,234.09
3	H. T. Yang, P. C. Yang [27]	Evolutionary Programming (EP)	8,234.07
4	J. B. Park, K. S. Lee [28]	Modified Particle Swarm Optimization (MPSO)	8,234.07
5	Ying-Ping Chen, Wen-Chih Peng [29]	Particle Swarm Optimization with ecombination and dynamic linkage discovery (PSO-RD)	8,234.07
6	This paper	Fully Informed Particle Swarm Optimization	8,233.85

Table 7
Time Comparison of PSO and FIPSO

	Time (s)	
Power System Benchmark	PSO	FIPSO
IEEE 3 Bus	0.52	0.49
IEEE 30 Bus	4.85	3.96

computational time and least values of cost and emission functions show the superiority of the proposed algorithm in comparison to PSO. In addition, ED problem is also solved separately by using IEEE 30-bus three-generator system with valve-point loading effect, and its performance is compared with GA, IEP, EP, MIPSO and PSO-RD. Results section substantiates that fuel costs are also decreased to a great extent by proposed FIPSO in comparisons to the above heuristic approaches. Therefore, proposed algorithm proves to be very effective in terms of reducing fuel cost and emissions for thermal power plants. In the future, FIPSO can become very competitive technique in optimal power flow and various multi-objective optimization issues.

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Biographies

Muhammad F. Tahir received the B.Sc. degree in electrical engineering from the University of Engineering and Technology Taxila, Taxila, Pakistan, in 2011, M.S. degree in electrical engineering from The University of Lahore, Lahore, Pakistan, in 2015, and the Ph.D. degree in Power System and Automation from South China University of Technology, in 2020. From 2012 to 2016, he was a Lecturer with The University of Lahore. He is currently a postdoctoral fellow in South China University of Technology, Guangzhou, China.

Kashif Mehmood received B.S (Hons.) and MS (Hons.) in Electrical Engineering from The University of Lahore, Pakistan in 2011 and 2015, respectively. In 2012, he joined The University of Lahore, Electrical Engineering Department, and now he is serving as a research associate in IeCe Lab, Mechanical Engineering Department. He is currently pursuing the Ph.D. degree from Southeast University Nanjing, Jiangsu China.

Chen Haoyong received B.S, M.S.E and Ph.D. in Electrical Engineering from Xi'an Jiaotong University in 1995, 1997 and 2000, respectively. An influential professor of electrical engineering (in both academia and industry) with 14 years' research and teaching experience as a university faculty member of electrical engineering. Director of Institute of Power Economics and Electricity Markets, South China University of Technology. Excellent research record on modeling/optimization/control of power systems and electricity markets.

Atif Iqbal completed the Ph.D. degree in renewable energy and clean energy from the North China Electric power University, Beijing, China in 2021. Currently, he is working on the shanxi science project with the renowned professor Tian De.

Dr. Adeel Saleem received his B.Sc. degree in electrical engineering from The University of Lahore, Lahore, Pakistan, in 2011. He was awarded the Gold Medal in his bachelor's degree. He did his M.Sc. in electrical engineering from The University of Lahore, Lahore, Pakistan, in 2015 and again was awarded with the Gold Medal. Now he has received his Ph.D. degree in electrical engineering from the North China Electric Power University, Beijing, China in 2021.

Shaheer Shaheen received B.Sc. degree in electronics engineering from Balochistan University of Information Technology, Engineering and Management Sciences, Quetta, Balochistan, Pakistan, M.Sc. degree from University of Lahore, Lahore. Pakistan in 2019. He is currently working in SNGPL.