Chapter 27
Combined Environmental and Economic Dispatch in the Presence of Sustainable Sources Using Particle Swarm Optimization with Adaptive Weighted Delay Velocity

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Abstract Recently, the excessive utilization of fossil fuels in power plants requires the concern of environmental safety. In general, the economic power dispatch (ED) does not convene environmental safety as its major intention is a reduction of the overall generation cost of the system. The accurate solution of economic dispatch is acquired only by concerning the environmental issues. So ED becomes combined environmental and economic dispatch (CEED) with cost and emission as two objective functions. In this study, particle swarm optimization (PSO) with adaptive weighted delay velocity (PSO-AWDV) algorithm is used for solving the CEED dilemma for a coordinated ten thermal unit and sustainable energy sources like wind and solar system with weighting method and fuzzy decision-making (FDM) method. The obtained outcomes indicate the inclusion of sustainable sources with the thermal units is more economical as compared to the thermal system, and the outcomes are correlated with PSO, sparrow search algorithm (SSA), sequential quadratic programming (SQP), evolutionary programming (EP), and hybrid of SQP and EP.

Keywords CEED · PSO-AWDV · Renewable energy sources (RES) · FDM · ED · Emission dispatch

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1 Introduction

Combined environmental and economic dispatch (CEED) is the online practice of allocation of the load among the accessible generators to accomplish the load demand with the reduction of net generation cost and emission with fulfilling the system bounds. The prime goal is the economical operation of the power system so that all the load demand is fulfilled at the minimum cost of generation and emission of harmful gases like CO_2, SO_2, and NO_X. In this work, the PSO-AWDV method is used to solve this CEED dilemma.

Kennedy and R. Eberhart have introduced PSO. PSO was projected to decipher the multi-objective dilemma in [1]. Hybrid particle swarm optimization (HPSO) algorithm is employed to decipher the CEED dilemma in [2]. Advanced PSO (APSO) is applied to explain the CEED problem in [3]. Solar generating systems (SGS) are considered on CEED of the power system in [4]. The consequence of wind on CEED has been discussed in [5]. The non-dominated sorting genetic algorithm-II is applied for explaining the DEED dilemma of a hydro–wind–thermal power system in [6]. Phasor particle swarm optimization (PPSO) is proposed to explain economic load dispatch (ELD) dilemmas with several system bounds [7]. The dynamic economic dispatch (DED) dilemma with valve point effects (VPE) has been discussed in [8]. The constriction factor-based particle swarm optimization (CFBPSO) algorithm is employed to solve the CEED dilemma of a thermal–wind–solar power system with dynamical load demand [9]. A ten thermal units system with RESs is thoroughly analyzed for dynamic CEED [10]. The major handouts of this work are: (1) A novel PSO with adaptive weighted delay velocity (PSO-AWDV) is flourished by adaptively revising the velocity inertia weight of the PSO-WDV algorithm which offers some supremacy to the particles to overcome from the local trap. [11]. (2) The supremacy of the projected algorithm is investigated with some earlier developed optimization algorithms like SSA [12], PSO [1], SQP, EP, EP-SQP method [13] and are applied to decipher the CEED dilemma of a ten thermal unit with sequential quadratic programming sustainable energy sources like wind and solar energy source. (3) The multi-objective CEED dilemma can be changed to a solo objective with the weighting function method [14]. The section-wise organization of the paper is given below:

Sect. 2 describes the formulation of load dispatch problem, Sect. 3 describes CEED using PSO-AWDV, Sect. 4 explains the case studies and results obtained, and Sect. 5 finally concludes the research work and shows the future scope for further research.

2 Optimal Load Dispatch Problem Formulation

2.1 Problem Formulation for Economic Dispatch (ED)

The ED dilemma in power systems is to share the load among the devoted generator unit in such a fashion that the cost of generation is reduced by appeasing the load demand and system bounds.

The minimum fuel cost of i th unit is formulated as:

$$F_c(P_i) = a_i * P_i^2 + b_i P_i + c_i \$/h \tag{1}$$

Subject to:

(a) Equality constraints

$$\left(\left(\sum_{i=1}^{n} P_i\right) - P_{\mathrm{L}} - P_{\mathrm{D}}\right) = 0 \tag{2}$$

where

a_i, b_i, c_i	are coefficients of cost of ith thermal unit (TU)
P_i	is power generation of ith unit
n	is the total figure of TUs.

P_{L} indicates the power loss which is neglected here, P_{D} is load demand, and n is the maximum number of thermal units.

2.2 Problem Formulation for Emission Dispatch

The emission released from a power plant should be within a permitted limit and the emission constraint can likewise be taken as in (3).

$$E_m(P_i) = \alpha_i * P_i^2 + \beta_i P_i + \gamma_i P_i^2 + \varepsilon_i \times \exp^{(\delta i \times Pi)} \text{ kg/h} \tag{3}$$

where α_i, β_i, γ_i, ε_i, and δ_i are coefficients of GHGs emission of ith unit, exp is an exponential function.

2.3 Problem Formulation for CEED

The weighting function method is applied to convert the multi-objective dilemma into a single objective as in (4)

$$\text{Min } F_T = \sum_{i=1}^{n} (w_1 F_c(P_i) + w_2 E_m(P_i)) \tag{4}$$

where F_T is a combined objective function to be limited. When all the sources are considered, then the combined objective function is as in (5)

$$\text{Min } F_T = F_i(P_i) + E_i(P_i) \tag{5}$$

where $F_i(P_i)$ and $E_i(P_i)$ are the total generation cost and total emission cost of thermal, wind, and solar plant, respectively.

Subject to:

$$\begin{aligned} & P_D + P_L - \sum_{i=1}^{n} P_i - \sum_{j=1}^{m} P_{gsj} - \sum_{z=1}^{q} P_{gwz} = 0 \\ & P_{i\ \min} \leq P_i \leq P_{i\ \max} \end{aligned} \tag{6}$$

$P_{i\ \min}$ is the lowest and $P_{i\ \max}$ is the highest generation limit of ith unit in MW.

where P_{gsj} is power accessible from jth solar plant and P_{gwz} is power available from zth wind plant. The solar and wind power plant sharing the load with m and q generating units, respectively.

The effect of valve point loading (VPE) can be modeled by adding a sinusoidal term to the main cost function as in (7)

$$F_c(P_i) = \sum_{i=0}^{Ng} \left(a_i * P_i^2 + b_i P_i + c_i\right) + |d_i \sin(e_i * (P_{i\ \min} - P_i))| \quad [\$/h] \tag{7}$$

d_i, e_i are the coefficients of VPE of the i th unit. $P_{i\ \min}$ is the minimum generation limit of i th unit in MW.

3 CEED Using PSO-AWDV Technique

3.1 Formulation of PSO with Adaptive Weighted Delay Velocity

In the search space, the velocity and position influence the search behavior of PSO. The particles are updated as per the following equations.

$$v_i^{(r+1)} = w * v_i^{(t)} + c_1 * r_1 * (x_{ip\,\text{best}}^{(t)} - x_i^{(t)}) + c_2 * r_2 * (x_{ig\text{best}}^{(t)} - x_i^{(t)}) \quad (8)$$

$$x_i^{(t+1)} = x_i^{(t)} + v_i^{(t+1)} \quad (9)$$

where t is maximum iterations (generations), w is inertia weight factor.

c_1, c_2 are learning factors, r_1, r_2 are random values in the range [0–1].

$v_i^{(t)}$ is velocity of particle i at iteration t and $x_i^{(t)}$ is current position of particle at iteration t. $v_i^{(t+1)}$ and $x_i^{(t+1)}$ are new velocity and position of particle i, respectively.

Inertia weight is revised after each iteration and is expressed as in (10)

$$w = w_{\max} - \frac{w_{\max} - w_{\min}}{t_{\max}} * t \quad (10)$$

where $w_{\max}$ and $w_{\min}$ are the highest and lowest value of inertia weight. $t_{\max}$ is maximum number of iterations. The flowchart of PSO-AWDV algorithm for dispatch problem is Fig. 1.

The updating functions of PSO-AWDV are

$$v_i^{(t+1)} = w * v_i^{(t)} + (1 - w) * v_i^{(t-1)} + c_1 * r_1 * (x_{ip\text{best}}^{(t)} - x_i^{(t)}) + c_2 * r_2 * (x_{ig\text{best}}^{(t)} - x_i^{(t)}) \quad (11)$$

$$x_i^{(t+1)} = x_i^{(t)} + v_i^{(t+1)} \quad (12)$$

$x_{ip\text{best}}^{(t)}$ and $x_{ig\text{best}}^{(t)}$ are the best positions experienced by the ith particle and the particle swarm up to the current iteration.

where c_1, c_2 are cognitive and social acceleration factors, *rand*, *Rand* are random numbers arbitrarily chosen between 0 and 1.

w is the inertia weight of the velocity $v_{ipbest}^{(t)}$ and $w < 1$; $(1 - w)$ is the inertia weight of the delayed velocity $v_i^{(t-1)}$.

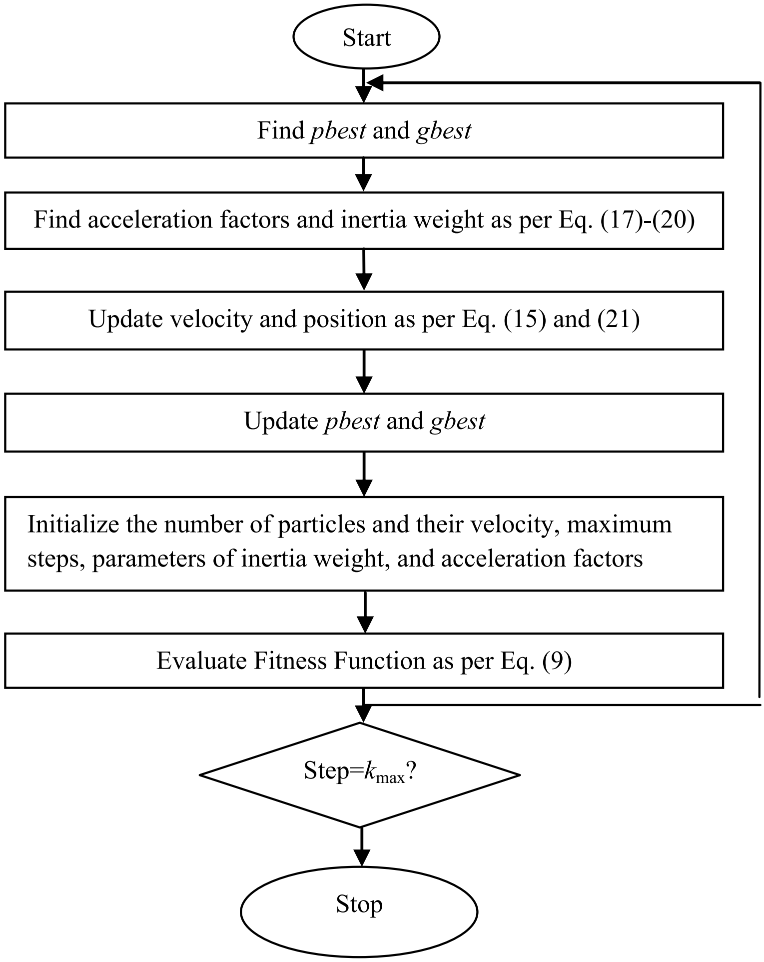

Fig. 1 Flowchart of PSO-AWDV

4 Case Studies and Simulation Results

4.1 Ten Thermal Units Without VPE: Case 1

In this scenario, PSO-AWDV is implemented to decipher the CEED dilemma for minimizing the fuel and emission cost for ten number of thermal generating units (TUs) without considering VPE. The hourly system load demand and the generator cost coefficients of ten units thermal system as in [8] and emission coefficients of ten units thermal system as in [15] (Table 1).

Table 1 Result for Case 1 with FDM method

Weighting functions		CEED cost	Fuel cost	Emission cost	Membership function		Accomplishment function
w_1	w_2	C	F	E	μ_1	μ_2	μ_d^k
1	0	1,007,408.41	1,007,408.45	31,280.31	0.9664	0.0736	0.0425
0.95	0.05	958,933.66	1,007,731.9	31,767.54	0.9509	0	0.0388
0.9	0.1	909,551.37	1,007,085.24	31,746.62	0.9819	0.0032	0.0402
0.85	0.15	860,389.99	1,006,708.49	31,251.84	1	0.078	0.044
0.8	0.2	812,169.65	1,007,440.35	31,086.86	0.9649	0.1029	0.0436
0.75	0.25	761,567.1	1,006,886.54	31,610.46	0.9915	0.0237	0.0415
0.7	0.3	713,573.08	1,008,942.93	30,941.39	0.8927	0.1249	0.0415
0.65	0.35	664,848.59	1,007,633.06	30,851.31	0.9556	0.1385	0.0447
0.6	0.4	614,627.39	1,007,184.11	31,011.39	0.9772	0.1143	0.0446
0.55	0.45	567,974.85	1,007,939.11	30,240.74	0.9409	0.2308	0.0478
0.5	0.5	518,835.09	1,007,743.12	29,927.07	0.9503	0.2782	0.0502
0.45	0.55	468,220.44	1,007,704.49	29,623.29	0.9522	0.3241	0.0521
0.4	0.6	421,075.7	1,008,680.17	29,339.39	0.9053	0.367	0.052
0.35	0.65	371,962.65	1,009,387.6	28,733.85	0.8714	0.4586	0.0543
0.3	0.7	322,821.15	1,010,457.76	28,119.78	0.82	0.5514	0.056
0.25	0.75	273,598.08	1,011,902.57	27,496.59	0.7506	0.6456	0.057
0.2	0.8	224,217.7	1,013,612.4	26,994.95	0.6686	0.7214	0.0568
0.15	0.85	174,397.15	1,016,733.97	26,253.75	0.5187	0.8334	0.0552
0.1	*0.9*	*125,790.56*	*1,020,160.48*	*25,661.7*	*0.3542*	*0.9229*	*0.0581*
0.05	0.95	75,320.03	1,025,208.9	25,325.88	0.1118	0.9737	0.0443
0	1	25,151.84	1,027,538.2	25,151.84	0	1	0.0408

In this scenario, PSO-AWDV is implemented to decipher the CEED dilemma for minimizing the fuel and emission cost for ten number of thermal generating units without considering VPE. The hourly system load demand and the generator cost coefficients of ten thermal units system as in [8] and emission coefficients of ten thermal units system as in [15].

4.2 Ten Thermal Units with VPE: Case 2

In this case, PSO-AWDV is implemented to solve the CEED problem for minimizing the fuel and emission cost for ten number of thermal generating units considering VPE. The best-compromised result obtained by applying the FDM method in Case 2 is displayed in Table 2. It is observed that the obtained outcomes are slightly increased than the earlier case1 when the VPE of the thermal system is taken into

Table 2 Results of the power ratings for CEED for the ten thermal system in Case 2

Time (h)	P_1 (MW)	P_2 (MW)	P_3 (MW)	P_4 (MW)	P_5 (MW)	P_6 (MW)	P_7 (MW)	P_8 (MW)	P_9 (MW)	P_{10} (MW)	Cost ($)	Emission (ton)
1	150	135	97.88	96.25	120.61	131.93	95.08	74.7	79.52	55	30,022	360.71
2	163.91	152.41	101.94	96.32	150.54	131.22	95.21	105.3	58.11	55	32,444.19	410.44
3	247.96	155.04	111.03	116.58	167.24	153.83	82	94.11	75.16	55	36,000.72	532.18
4	221.73	198.48	134.09	134.86	184.92	158.48	119.9	118.48	80	55	39,006.37	630.66
5	216.68	212.86	146.18	146.47	212.78	160	130	120	80	55	40,123.86	701.61
6	329.92	248.16	157.05	158.05	214.06	135.73	130	120	80	55	41,294.6	921.74
7	241.1	312.4	183.24	177.24	243	160	130	120	80	55	41,326.88	990.41
8	296.45	296.21	197.65	197.67	243	160	130	120	80	55	41,474.01	1011.67
9	335.39	311	270.2	222.17	243	157.22	130	120	80	55	48,211.3	1270.99
10	388.13	388.13	253.86	253.86	243	160	130	120	80	55	50,179.41	1651.47
11	410.96	411.03	268.04	267.96	243	160	130	120	80	55	50,132.81	1813.9
12	183.01	460	340	300	243	160	130	120	80	55	50,133.74	2044.28
13	388.13	388.12	253.86	253.87	243	160	130	120	80	55	50,172.75	1647.47
14	342.27	342.11	225.73	225.86	243	160	130	120	80	55	50,602.27	1352.39
15	337.91	266.93	179.63	205.35	242.82	160	128.3	119.99	80	55	45,281.43	1102.09
16	269.33	228.52	158.5	166.99	195.09	155.87	126.5	119.67	78.48	55	42,107.01	802.25
17	209.6	239.01	145.92	144.54	199	159.74	130	119.44	77.71	55	40,551.59	702.42
18	312.87	261.25	177.56	167.33	206.89	160	94.27	112.83	79.95	55	42,092.47	925.00
19	268.22	332.19	188.16	199.41	243	160	130	120	80	55	41,981.05	1102.62
20	325.72	426.25	309.24	222.77	243	160	130	119.99	80	55	50,451.93	1691.69
21	330.26	335.65	251.46	218.62	243	160	130	119.99	80	55	50,520.08	1360.6

(continued)

Table 2 (continued)

Time (h)	P_1 (MW)	P_2 (MW)	P_3 (MW)	P_4 (MW)	P_5 (MW)	P_6 (MW)	P_7 (MW)	P_8 (MW)	P_9 (MW)	P_{10} (MW)	Cost ($)	Emission (ton)
22	299.12	241.31	169.78	170.53	222.83	160	125	104.39	80	55	41,404.15	901.93
23	158.88	215.54	131.7	140.87	198.29	158.09	79.44	114.16	80	55	37,641.46	581.51
24	150	203.39	140.58	97.01	146.87	132.5	96.23	100.75	61.63	55	33,961.64	471.54
Using PSO-AWDV Total =											1,027,117.72	24,981.57
Using PSO =											1,027,316.72	25,068.57
Using SSA											1,027,472.23	25,188.28
Using hybrid EP and SQP [13]											1,035,748.00	
Using EP [13]											1,048,638,481	
Using SQP [13]											1,051,163.00	

consideration. The fuel cost obtained by the projected method is less as compared to sparrow search algorithm (SSA), PSO, SQP, EP, and hybrid of EP and SQP method. It is realized from the outcomes that the projected method is quite effective in solving the CEED problem.

4.3 Ten Thermal Units with VPE + Wind Plant: Case 3

In this case, PSO-AWDV is implemented to solve the CEED problem for minimizing the fuel and emission cost for ten number of TUs with VPEs and a wind plant. The capacity of wind and solar plants is considered as 30 and 40 MW, respectively [15, 16]. The result obtained in Case 3 at $w_1 = 0.05$, $w_2 = 0.95$ is CEED total cost, fuel cost, and emission 125,750.7 \$, 1,021,313.55 \$, and 25,609.59 ton, respectively. The outcomes give evidence that the projected approach is quite effective in solving the CEED problem.

4.4 Ten Thermal Units with VPE + Solar Plant: Case 4

In this case, PSO-AWDV is implemented to solve the CEED problem for minimizing the fuel and emission cost for ten number of TUs considering VPEs with solar and emission impact. The best-compromised result obtained at $w_1 = 0.15$, $w_2 = 0.85$ is the CEED total cost, fuel cost, and emission 127,045.7 \$,1,022,885.5 \$, and 27,029.4 ton, respectively.

4.5 Ten Thermal Units with VPE + Wind + Solar Plant: Case 5

In this case, PSO-AWDV is implemented to solve the CEED problem for minimizing the fuel and emission cost for ten number of thermal generating units considering VPE with both renewable energy sources (solar and wind). Table 3 demonstrates the real power ratings for the 10 generators in this scenario at $w_1 = 0.1$, $w_2 = 0.9$. The convergence plot of this case is displayed in Fig. 2, and it is realized from the figure that the projected method is quite effective in solving the CEED problem.

In case 2, when VPE of thermal units is considered, then cost increases but more practical results are obtained. In case 3, when wind source is included with the thermal system, both cost and emission are reduced. Similarly, in case 4 when a solar source is included with the thermal system, both cost and emission are reduced. In case 4, cost and emission are slight increases as compared to case 3. The comparison of all cases is exhibited in Table 4 and in Figs. 3 and 4, respectively. It is observed that in

Table 3 Results of the power ratings for CEED for the ten thermal system in Case 5

Time	P_1 (MW)	P_2 (MW)	P_3 (MW)	P_4 (MW)	P_5 (MW)	P_6 (MW)	P_7 (MW)	P_8 (MW)	P_9 (MW)	P_{10} (MW)	Cost	Emission	CEED
(hr)	MW	MW	MW	MW	MW	MW	MW	MW	MW	MW	($)	(ton)	($)
1	150.00	135.00	73.03	120.42	172.73	145.15	93.06	47.00	20.00	55.00	28,232.71	403.32	3180.95
2	287.96	135.02	73.01	66.25	172.58	122.48	94.03	47.00	20.00	55.00	29,642.35	428.98	3424.05
3	150.00	222.20	157.52	113.26	172.72	123.13	130.00	47.14	52.07	55.00	32,864.61	470.98	3774.71
4	226.24	309.58	185.14	126.28	122.73	122.67	93.25	85.32	52.06	55.00	36,223.96	627.13	4286.01
5	155.54	309.53	259.22	176.30	122.90	131.07	129.97	85.31	52.06	55.00	38,702.88	670.52	4673.47
6	303.18	222.63	185.25	179.53	209.50	159.93	129.61	119.99	52.06	55.00	41,894.62	884.35	5013.02
7	379.87	309.30	185.32	120.49	181.37	149.63	130.00	120.00	52.10	55.00	43,138.19	1022.92	5288.11
8	303.16	309.58	200.38	226.41	222.59	126.39	129.62	120.00	52.06	55.00	44,727.43	1120.76	5493.08
9	303.25	396.80	184.87	236.64	222.60	160.00	129.59	120.00	80.00	55.00	48,179.25	1261.36	6012.22
10	303.23	396.93	292.37	241.09	231.28	160.00	129.61	120.00	80.00	55.00	50,869.11	1529.63	6494.42
11	379.89	396.80	278.60	241.18	225.14	160.00	129.70	120.00	79.99	55.00	52,137.17	1601.71	6713.84
12	379.88	460.00	297.40	241.26	241.88	160.00	129.59	85.32	80.00	55.00	53,836.54	1652.68	7065.54
13	303.25	396.80	186.38	300.00	243.00	160.00	130.00	120.00	80.00	55.00	50,452.17	1502.30	6396.79
14	379.87	309.53	193.24	180.94	222.73	160.00	129.73	120.00	80.00	55.00	46,828.53	1208.63	5778.90
15	379.93	222.28	203.54	180.84	222.74	160.00	101.67	85.31	80.00	55.00	44,045.77	1132.64	5369.53
16	226.64	309.55	190.21	126.19	172.88	160.00	99.84	85.33	80.00	55.00	39,766.00	902.64	4704.43
17	276.75	222.22	182.88	120.41	222.45	122.46	93.06	85.29	52.05	55.00	37,769.83	791.74	4454.29
18	371.88	387.06	174.29	120.55	172.12	122.65	93.25	54.84	51.72	55.00	41,628.95	910.12	5176.22
19	226.59	309.25	295.87	179.35	222.31	159.90	130.00	119.54	52.01	55.00	44,504.67	1171.04	5502.97
20	456.49	396.80	188.83	300.00	223.34	132.59	129.65	85.40	80.00	55.00	51,596.52	1601.84	6752.81

(continued)

Table 3 (continued)

Time	P_1 (MW)	P_2 (MW)	P_3 (MW)	P_4 (MW)	P_5 (MW)	P_6 (MW)	P_7 (MW)	P_8 (MW)	P_9 (MW)	P_{10} (MW)	Cost	Emission	CEED
21	303.25	309.52	285.19	240.55	240.96	159.93	129.59	120.00	80.00	55.00	49,215.32	1400.52	6168.32
22	301.26	309.50	182.63	177.57	172.71	124.31	129.46	118.34	51.93	55.00	41,759.55	1011.69	5050.18
23	150.00	288.67	181.53	179.12	122.83	122.19	93.16	84.78	50.40	55.00	35,676.01	630.41	4186.22
24	226.62	135.00	185.22	62.67	122.89	129.33	129.86	85.34	52.07	55.00	31,774.22	550.79	3654.55
										Total =	1,015,466.35	24,488.80	124,614.63

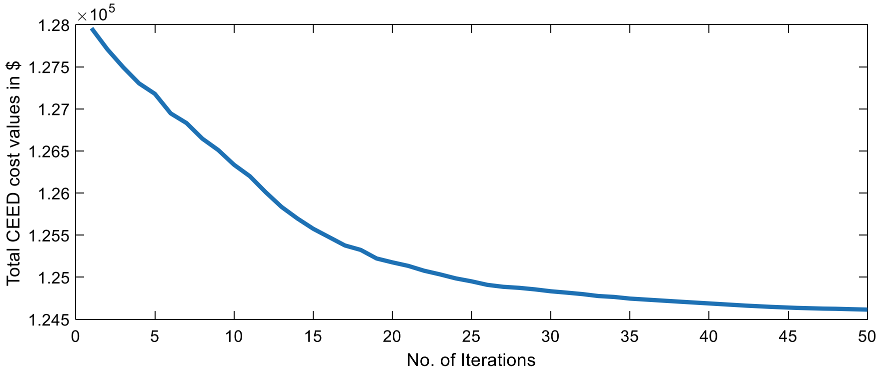

Fig. 2 Convergence characteristic for Case 5

Table 4 Analogy of all cases concerning cost, emission, and CEED total cost

Case	Cost in $	Emission in ton	CEED Total cost in $
Case 1(only Thermal without VPE)	1,020,160.48	25,661.7	125,790.56
Case 2(only Thermal with VPE)	1,027,117.72	24,981.57	127,011.2
Case 3 (Thermal with VPE + Wind)	1,021,313.55	25,609.45	125,750.7
Case 4(Thermal with VPE + Solar)	1,022,885.5	27,029.27	126,407.7
Case 5(Thermal with VPE + Wind + Solar)	1,015,466.35	24,488.80	124,614.63

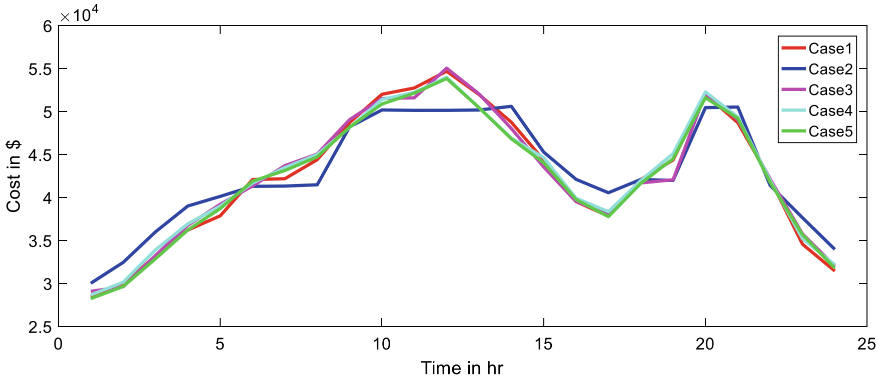

Fig. 3 Analogy of all cases concerning to cost

case 5 when both conventional and renewable energy sources are considered cost, emission, and CEED cost reduces as compared to all the four cases, and the proposed algorithm PSO-AWDV gives better outcomes as compared to other algorithms like SSA, PSO, SQP, EP, and EP-SQP and is presented in Fig. 5.

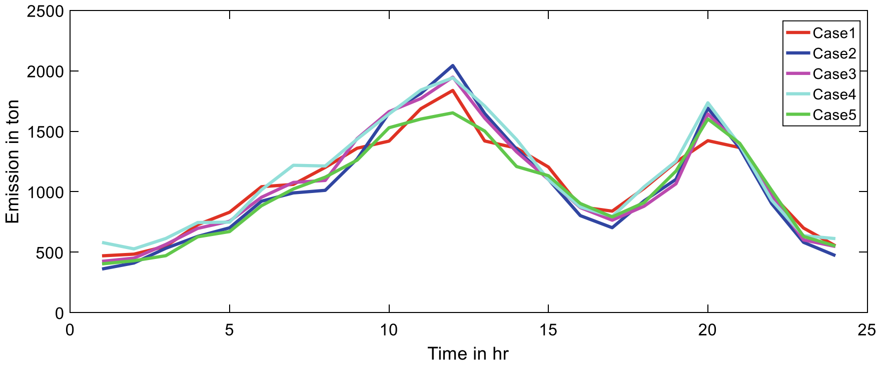

Fig. 4 Analogy of all cases concerning to emission

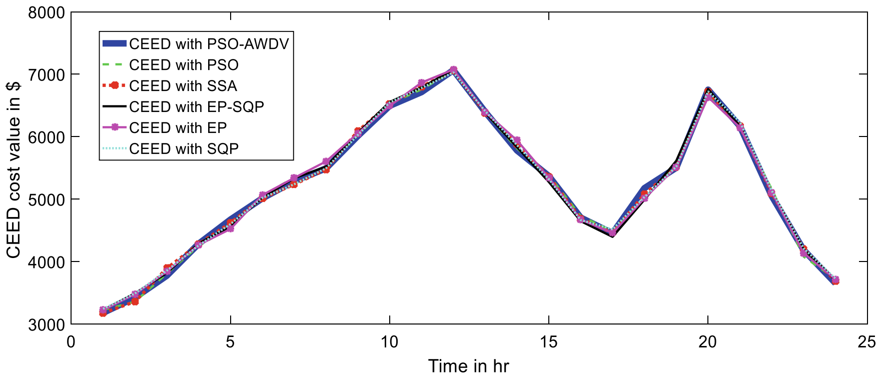

Fig. 5 Discrimination of all algorithms for Case 5 concerning to CEED cost value

5 Conclusion

This work offers the PSO algorithm with adaptive weighted delay velocity to solve the CEED dilemma. The CEED problem has been successfully solved by PSO-AWDV which minimizes generation cost and emission. The efficacy of the PSO-AWDV algorithm is tested in a complicated scenario, where sustainable sources and valve point effect are considered. It is noticed that net generation cost and emission both reduce in the scenario when we considered thermal and both sustainable sources. Also, the dynamic variation of load at the demand side is considered, and the generators' power dispatch within 24 h is described. The outcomes prove the efficacy of the projected method for the solution of the CEED dilemma. The areas that can be are researched further are: application to larger test systems, like 60 - generator, 100 - generator test to examine how the algorithm reacts in those scenarios and application to real systems such as actual power systems and power pools to realize its full benefit to society.

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