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The Dynamic Economic Dispatch in An Integrated Wind-Thermal Electricity Market Using Simulated Annealing Algorithm

***Abstract**. This paper proposes simulated annealing (SA) algorithm to solve the bid based dynamic economic dispatch (BBDED) problem with wind energy integration to study the performance and the economic benefit of wind energy integration in a deregulated electricity market. The proposed method is tested for convergence, robustness, and efficiency applied on a 10-unit test system with 12-period load demand. The results obtained are compared with other relevant methods, considering different constraints like power balance, generation limits, and ramp rate limits.*

Streszczenie.** Zaproponowano algorytm symulowanego wyżarzania problemu bazującego na ofercie ekonomicznego rozsyłu energii. Rozważano przypadek dołączonej do systemu energii wiatrowej I nieregulowanego rynku energii. Analizowano niezawodność I skuteczność na przykładzie systemu z 10 jednostkami. **Ekonomiczny rozsył energii w zintegrowanym z energetyką wiatrową rynkiem metodą symulowanego wyżarzania

Keywords: Deregulated electricity market, Bid based dynamic economic dispatch, Wind energy, Simulated annealing algorithm
Słowa kluczowe: ekonomiczny rozsył energii, energetyka wiatrowa, zderegulowany rynek, symulowane wyżarzanie.

Introduction

The objective of the deregulation of power systems is to reduce the electricity cost charged to the consumer considerably while ensuring the economic profitability for the generation company (GENCO) without affecting the system's stability, reliability, and security. The deregulated electricity market, which involves competition and customers' choice, is aided by an open system for power trading. [1] In competitive electricity markets, the generating company tries to maximize its profits by submitting supply bid for each period, which is the minimum acceptable unit price of electricity to satisfy the customers demand based on the bidding behaviour of the other participants and the operating conditions of the power system. According to the pre-determined electricity market clearing, a market operator, known as the Independent system operator (ISO), will determine the market price and the dispatched power of each generation company to the customer corresponding to the most economical operation with the objective of social profit maximization. [2] Wind power is among the most rapidly growing sources of renewable energies recently. In the deregulated electricity market where wind energy is being penetrated, the uncertainty and the intermittent nature of this resource make its integration difficult and non-dispatchable into the electricity market and power systems operation. Besides, the strategic interaction between wind-energy generators with other participants in the market like thermal GENCOs has introduced new complexities into the electricity market dispatch, which is the essential tool for analysis, design, and bidding for electricity market modelling and optimization. The objective of all participants in the electricity market bidding is the profit maximization. Wind power and other renewable energy sources usually have a low marginal cost, making them participate in the electricity market as "price takers" and improving the social profit of participants in the electricity market. Furthermore, the unpredictable nature of wind power means that it generally does not reach its production level, increasing the risk of system imbalances between supply and demand. Therefore, the only bidding parameter that the wind power must determine in the electricity market is its production level. [3, 4] The electricity market clearing mechanism is mainly based on bid-based dynamic economic dispatch, which is an extension of dynamic economic dispatch (DED) that is a bi-level optimization problem that treats two objectives functions, the generation cost minimization and the social profit maximization of GENCOs. It is performed by the ISO after receiving supply and demand bids from GENCOs and customers. DED is among the most important optimization problems that study the integration of renewable sources like wind energy in power systems. The DED is applied for determining the scheduling of generation units to satisfy load demand at the minimal cost of operation under a variety of constraints over all periods of bid based dispatch. [5] A conventional economic dispatch that integrates wind energy for optimal cost and energy optimization is presented in [6]. It involves under-estimation and over-estimation of wind power available in the optimum schedule of generators. A similar model is presented in [7]. In [8], the economic dispatch problem is solved considering the conventional and wind GENCOs using fuzzy logic to maximize the wind energy penetration and without undermining conventional generators, where the maximization of social profit is achieved. Various researchers have proposed various methods like isolation niche immune genetic algorithm (INIGA) [9], genetic algorithm (GA) [10], efficient interior-point (IP) algorithm [11], particle swarm optimization (PSO), linear programming (LP) [12], and, multi-echelon (ME) [13] to solve different BBDED problems. This paper solves the BBDED problem using the simulated annealing algorithm, which is implemented and adopted in MATLAB and compared to other methods. In the first study, the BBDED is solved using a conventional power system. In the second study, it is solved using an integrated wind-thermal power system to study the impact of wind energy integration and analyse its economic benefit in the electricity market.

Problem formulation

The objective of the BBDED is to determine the optimum schedule of generation units with the minimum cost to maximize the social profit of participants. It is formulated with the received supply and demand bids from the generating companies and customers.

A. Objective function

The objective function of the BBDED problem can be modelled with the following expression:

(1) $$\mathrm{Max}\left(\mathrm{PF}\right) = \sum_{t=1}^{T} \left[\sum_{j=1}^{Nc} B_j\left(D_{j,t}\right) - \sum_{i=1}^{Ng} C_i\left(Pg_{i,t}\right) \right]$$

(2) $$B_j\left(D_{j,t}\right) = a_{dj} D_{j,t}^{\,2} + b_{dj} D_{j,t} + c_{dj}$$

(3) $$C_i\left(Pg_{i,t}\right)=a_{gi}Pg_{i,t}^{\ 2}+b_{gi}Pg_{i,t}+c_{gi}$$

where, $B_j(D_{j,t})$ is demand bid function of customer *j*, $C_i(Pg_{i,t})$ is cost function (supply bid) of generator *i*, $D_{j,t}$ is bid quantity of customer *j* at period *t*, $Pg_{i,t}$ is bid quantity of conventional generator *i* at period *t*, N_c is the number of customers; N_g is the number of generators, a_{dj}, b_{dj}, c_{dj} are benefit coefficients of customer *j*, a_{gi}, b_{gi}, c_{gi} are cost coefficients of generator *i*, *T* is period number.

B. Problem constraints

These include constraints related to equality, inequality, and ramp rate limits.

Equality constraints

It is the typical equation for the balance of the active power flow from generators to loads, and is given as follows:

(4) $$\sum_{i=1}^{Ng}Pg_{i,t}=\sum_{j=1}^{Nc}D_{j,t}+P_L$$

where P_L is transmission losses that are represented with B-coefficients as follows:

(5) $$P_L=\sum_{i=1}^{Ng}\sum_{j=1}^{Ng}Pg_{i,t}B_{i,j}Pg_{j,t}+\sum_{I=1}^{Ng}B_{i,0}Pg_{i,t}+B_{0,0}$$

Inequality constraints

The energy generated by generators is between lower and upper limits. The generators are built to produce power within a secure band to avoid over-production or under-production during load demand satisfaction.

(6) $$Pg_{i,,t\min}\le Pg_{i,t}\le Pg_{i,t\max}$$

Demand-side bids are bounded to a maximum and a minimum to maintain a balance with the supply-side.

(7) $$D_{j,t\min}\le D_{j,t}\le D_{j,t\max}$$

Ramp rate limits constraints

The generated power by the generators is bounded within the ramp rate. It represents the rate of changing power generated by a generator, which can either increase (ramp-up) or decrease (ramp-down). It is therefore given in power units produced per period (MW per minute) and expressed as follows:

(8) $$DR_i\le Pg_{i,t}-Pg_{i,(t-1)}\le UR_i$$

where, DR_i is maximum decrease power (ramp-down) of the generator *i* during a period, UR_i is maximum increase power (ramp-up) of the generator *i* during a period.

C. Wind power

Wind energy is among the most important sources of renewable energy used globally and has been widely exploited in recent years. It has economic and environmental advantages, such as low investment costs and the absence of pollution. However, wind power generation depends mainly on wind speed, air density, swept area, generator efficiency, and air density. The value of the power coefficient depends on the wind speed and the rotation speed of the turbine. [14, 15] The mechanical output of a wind turbine can be expressed as follows:

(9) $$P_W=\frac{1}{2}C_p.\rho.\pi.R_P^2V_W^3$$

where, C_P is wind turbine power aerodynamic coefficient (it indicates the ability of the wind turbine to capture wind energy), ρ is the density of the air (1.225kg/m^3) R_P is the radius of the rotor in m, V_W is the wind speed in m/s.

Simulated annealing algorithm solution for the optimization problem

The simulated annealing (SA) technique was proposed for the first time in 1953 by Metropolis [16]. The technique is inspired by the similarity of the solid material annealing process and the global optimization problem. In 1983, S. Kirkpatrick [17] had effectively implemented the simulated annealing into a computational problem. This algorithm is inspired by nature and adopted from the metal cooling process in nature. The metal is first exposed to a high temperature where it turns into a liquid and then progressively cooled down to the solid form. All temperatures are held till the metal gets a thermo-hydraulic equilibrium and solidifies. The SA is a probabilistic method approximates the optimal global solution of a studied objective function. It is frequently applied if the searching field is a discrete one. Simulated annealing may be preferable for problems where the optimal global solution is more effective than the optimal local solution within a given time frame. Generally, at every time-step, the SA algorithm generates a random solution near the current solution, evaluates its quality, and then makes a decision to switch to this solution if it is a better solution or to keep this current one based on probability criterion. The simulated annealing mechanism includes controlled parameters such as initial temperature, temperature decrement factor, final temperature, and iterations at all temperatures, outlined below: [18, 19]

A. Initial temperature

The initial temperature should be chosen at a reasonably high degree because it will be acceptable in the first step of the algorithm implementation as a solution. However, when the initial temperature is higher, the SA step may not proceed due to the slow convergence, and, in general, the optimization process will be a bit randomized.

B. Final Temperature

When applying the SA algorithm commonly, the temperature is allowed to drop to 0 degrees. If the temperature drop turns into an exponent, the simulated annealing steps may work longer. Finally, the stop step can be a lower temperature or an appropriate point once the system is cooling down to the final temperature.

C. Temperature decrement factor

After the initial temperature has been defined, it is important to search for a technique to switch from initial to the final temperature. The way that the temperature is decreased is an essential part of the algorithm's performance. It is proposed to use the geometric decay equation to reduce the temperature as explained below:

(10) $$T^k=\alpha T_0$$

Where, k is the iterations number, α is the cooling coefficient of temperature, T_0 is the temperature in the initial state.

Moreover, the mechanism of the SA technique can be separated into several sections in the combinatorial optimization problem:

- Initialize a maximum temperature and the initial solution to the problem.
- Optimize the solution of the problem following the metropolis stopping criterion.
- Obtain optimum solutions.

The metropolis criterion is to accept the following solution with some probability and abandon the current solution when the solution obtained in the following iteration is deteriorated.

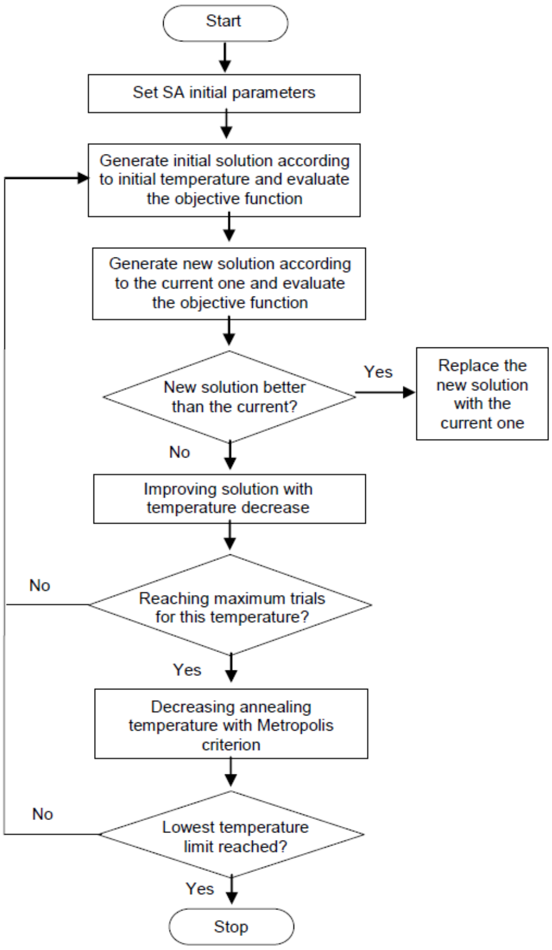

Fig.1. Simulated annealing algorithm flowchart

The acceptance probability is expressed as follows:

(11) $$P = \begin{cases} 1 & f^* \le f \\ \exp\left(\dfrac{f - f^*}{T}\right) & f^* > f \end{cases}$$

where f and f^* are the generated solutions from the current solution and the following iteration, respectively, T is the associated temperature, P is the probability function.
The SA step is continued as long as the temperature decreases to a defined minimum value. The proposed SA algorithm was implemented to solve the BBDED problem and described using the following flowchart, as shown in Fig. 1.

Results and discussion

The simulated annealing algorithm is proposed to solve the bid-based dynamic economic dispatch, which is applied to search and find the optimum solutions for various parameters such as production cost, customer benefit, and to calculate the social benefit of market participants. Table 1 presents the proposed SA algorithm parameters.

Table 1. The SA algorithm parameters

Parameter	Constant value
Initial temperature T_I	300 °C
Alpha α	0.99
Max tries	10 e3
Final temperature T_F	0.1 °C

A 10-unit test system is considered for the simulation, which includes 10 GENCOs and 6 customers for 12 trading periods with total capacity committed satisfying 12-hour load demands ranging from 1036 MW to 2220 MW as presented in Table 3. For the GENCOs, the fuel cost coefficients are taken as price bids to represent the supply-side bidding. For customers, the bid coefficients represent the demand-side bidding. The bid data were taken from [20] and given in Tables 2 and 3. Two study cases are considered in this part.

Study case 1: Bid based dispatch without wind power
Study case 2: Bid based dispatch with wind power integration

The simulated annealing algorithm was implemented and adopted in the MATLAB environment. The results of the SA algorithm are compared to the results obtained by the GA, PSO, and ABC algorithms in terms of production cost, customers benefit, social profit, and average computational time. The SA algorithm is run over 20 times to get the best results.

Table 2. Generators bid parameters

Unit	a_{gi} ($/MWh^2)	b_{gi} ($/MWh)	c_{gi} ($/h)	Pmax ($/h)	Pmin (MW)	URi (MW)	DRi (MW)
1	0.00043	21.60	958.20	470	150	80	80
2	0.00063	21.05	1313.60	460	135	80	80
3	0.00039	20.81	604.97	340	73	80	80
4	0.00070	23.90	471.60	300	60	50	50
5	0.00079	21.62	480.29	243	73	50	50
6	0.00056	17.87	601.75	160	57	50	50
7	0.00211	16.51	502.70	130	20	30	30
8	0.00480	23.23	639.40	120	47	30	30
9	0.10908	19.58	455.60	80	20	30	30
10	0.00951	22.54	692.40	55	55	30	30

Table 3. Customers bid parameters for 12 periods

Customers		D1	D2	D3	D**4**	D**5**	D**6**	Demand per period
a_{dj} ($/MWh^2)		0.1	0.099	0.097	0.094	0.093	0.09	
b_{dj} ($/MWh)		20	19	17	16	15	12	
Maximum load demand bids at each period	1	300	180	130	200	116	110	1036
	2	190	220	100	200	150	250	1110
	3	208	150	250	300	100	250	1258
	4	270	230	256	190	300	160	1406
	5	300	280	240	260	150	250	1480
	6	400	320	170	230	208	300	1628
	7	260	192	350	300	400	200	1702
	8	370	250	350	406	150	250	1776
	9	320	400	200	350	420	234	1924
	10	472	300	400	350	300	250	2072
	11	500	490	250	240	360	306	2146
	12	410	420	380	350	360	300	2220

After the market clearing, the daily generation power is shown in Table 4 for the generating companies. It can be seen that all GENCOs and customers respect power limits.
Table 2. Generators bid parameters

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Table 4. Results of bid-based dispatch without wind power

Hour	1	2	3	4	5	6	7	8	9	10	11	12
P_1 (MW)	150.37	150.09	150.41	150.24	150.24	236.68	285.88	347.01	408.73	469.96	469.98	469.93
P_2 (MW)	135.64	135.56	222.42	370.34	443.87	460	460	460	460	460	460	460
P_3 (MW)	204.43	278.99	340	340	340	340	340	340	340	340	340	340
P_4 (MW)	60	60.04	60	60	60	60.02	60.09	60.10	60	106.07	168.34	220.41
P_5 (MW)	73.38	73.25	73.09	73.28	73.75	119.20	143.92	156.74	243	243	243	243
P_6 (MW)	160	160	160	160	160	160	160	160	160	160	160	160
P_7 (MW)	130	130	130	130	130	130	130	130	130	130	130	130
P_8 (MW)	47	47	47.01	47.01	47.02	47.03	47.06	47.13	47.02	87.76	98.54	120
P_9 (MW)	20.12	20.04	20.04	20.11	20.09	20.04	20.02	20	20.22	20.19	21.12	21.64
P_{10} (MW)	55	55	55	55	55	55	55	55	55	55	55	55
Generation cost ($)	28007.73	29062.02	32697.10	35867.95	37463.66	40682.97	42298.24	43916.69	47162.59	50586.51	52369.64	52247.80
Customers benefit ($)	37837.31	38979.10	48191.40	56533.49	61230.70	73407.05	77230.03	84818.08	94916.24	107258.4	117198.80	117188.20
Social profit ($)	9829.58	9917.08	15494.3	20665.54	23767.04	32724.08	34931.79	40901.39	47753.65	56671.89	64829.16	64940.4

Study case 1: Bid based dispatch without wind power

The bid data of GENCOs and customers are taken as inputs in the proposed SA algorithm. In this study, participant bid quantities are dispatched optimally over 12 trading periods. The overall bid-based dispatch results are presented in Table 4 and Fig. 2.

The SA has dispatched the generating companies produced power with 19758 MW to satisfy the customers' demand during the 12-trading period.

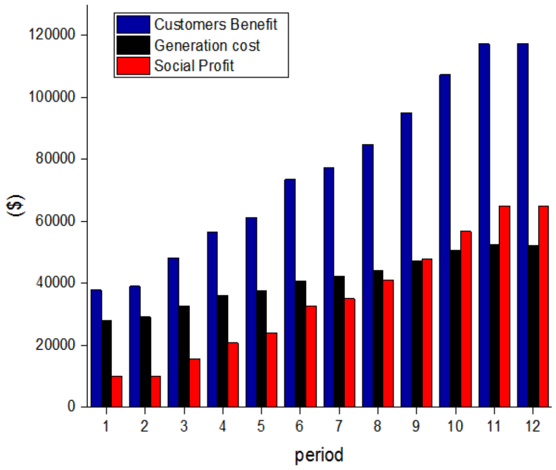

Fig.2. Outputs for 12 periods

From Fig. 2, it is clear that the social profit is maximized when the demand is increased. In this situation, the social profit is 9829.58 $ in period 1, which it is maximized over period 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12 with 87.5 $, 5664.72 $, 10835.96 $, 13937.46 $, 22894.5 $, 25102.21 $, 31071.81 $, 37924.07 $, 46842.31 $, 54999.58 $ and 55110.82 $, respectively, due to the higher received benefit in these periods and the optimization of generation cost. To verify and confirm the performance of the SA algorithm, the total bid-based dispatch results are compared to GA, PSO, and ABC approaches and presented in Table 5.

Table 5 has shown that the proposed SA method could obtain good solutions. It has performed better compared to other approaches by achieving a total social profit of 422425.90 $ which is higher than the GA, PSO, and, ABC approaches with 2691.08 $, 2406.79 $, and, 2437.65 $ respectively due to the optimized generation cost obtained with 492362.90 $ which is minimized than GA, PSO, and, ABC with 2691.12 $, 2406.79 $, and, 2437.65 $ respectively.

For the computational time, the proposed SA has outperformed the other methods with the fastest computation efficiency. The statistical and computational comparison indicates that the SA approach is feasible for providing better solutions than the other methods.

Table 5. Results comparison

Approach	Total Customers benefit ($)	Total Generation cost ($)	Total Social profit ($)	CPU time/interval (sec)
GA [10]	914788.85	495054.02	419734.82	-----
PSO	914788.80	494769.69	420019.11	24.21
ABC	914788.80	494800.55	419988.25	39.45
SA	914788.80	492362.90	422425.90	14.02

Study case 2: Bid based dispatch with wind power

In the case of the previous study, we have seen the effect of the demand variation on the BBDED problem, which causes a power imbalance between supply and demand, the increase in the generation cost, and social profit losses in the electricity market in some periods. In this case, a wind generator is integrated into the power system to see its impact on the BBDED problem, particularly on the generation cost and social profit with the variation in load demand during the electricity market clearing in the dispatch periods.

The wind generator that will be used will be integrated with a known or expected power, so the output power has a planned curve that is already computed based on a daily wind speed curve without being affected by the economic dispatching. For now, a wind farm has been integrated with 10.2 MW near the state of Adrar in Algeria, which has 10 turbines. The wind turbines model is Gamesa G52-850, with 850 KW of produced power [21]. It is expected to have 9 wind farms with the characteristics shown in Table 6 in the Algerian south-west region, generating approximately 100 MW.

Table 6. Characteristics of the wind generators

Wind Gen	a_{gi} ($/MWh^2)	b_{gi} ($/MWh)	c_{gi} ($/h)	Pmax ($/h)	Pmin (MW)	URi (MW)	DRi (MW)
P_w	0.002	0	0	100	0	100	100

A 12-period scenario is taken for the power produced by the wind farm located in the Adrar region, as presented in Fig. 3. The wind speed forecasted in this region is used for the calculation of the generated power in MW of the wind farms integrated into the Algerian south-west region for all 12 periods corresponding to the 12-time load period. [22].

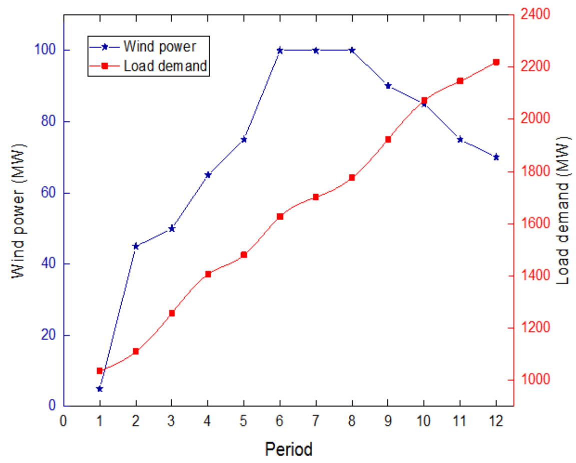

Fig.3. Forecasted wind power generation and load demand for 12 period

Two different objective functions are treated concurrently in this case, the minimization of the generation cost and the maximization of social profit of GENCOs. The simulation results are presented in Table 7 and Fig. 4 after the market-clearing with wind power integration during the 12-trading period.

From Table 7 below, we can see that when wind power integration has increased, the power outputs of the thermal units are simultaneously decreased, which affects the bid-based dispatch outcomes. From Fig. 4 below, it is clear that in this case, positive results can be seen. The integration of wind energy into the power system has improved and optimized the generation cost, which has led to the maximization of the social profit during the 12-trading period. Table 8 shows a comparison of the two study cases.

Table 7. Results of bid-based dispatch with wind power

Hour	1	2	3	4	5	6	7	8	9	10	11	12
P_1 (MW)	150.16	150.35	150.06	150.04	150.21	179.03	221.19	278.26	367.82	469.95	469.99	469.88
P_2 (MW)	135.49	135	172.77	305.77	369.37	460	460	460	460	460	460	460
P_3 (MW)	200.01	234.53	340	340	340	340	340	340	340	340	340	340
P_4 (MW)	60.07	60.03	60.02	60.03	60.01	60	60.01	60.04	60.03	60.08	71.02	180.95
P_5 (MW)	73.16	73	73.10	73.12	73.09	76.86	108.69	125.52	194.10	243	243	243
P_6 (MW)	160	160	160	160	160	160	160	160	160	160	160	160
P_7 (MW)	130	130	130	130	130	130	130	130	130	130	130	130
P_8 (MW)	47.03	47	47	47	47.25	47.03	47.02	47.16	47.03	47.49	120	89.45
P_9 (MW)	20.05	20.06	20.02	20.01	20.04	20.06	20.07	20	20	21.46	21.97	21.70
P_{10} (MW)	55	55	55	55	55	55	55	55	55	55	55	55
Generation cost ($)	27903.48	28620.51	31637	34480.19	35858.02	38525.24	40136.23	41750.55	45202.80	48565.26	50580.50	50476.39
Customers benefit ($)	37837.30	38979.10	48191.40	56533.49	61230.70	73407.05	77230.03	84818.08	94916.24	107258.4	117198.84	117188.20
Social profit ($)	9933.82	10358.58	16554.39	22053.29	25372.67	34881.80	37093.79	43067.53	49713.43	58693.13	66618.33	66711.81

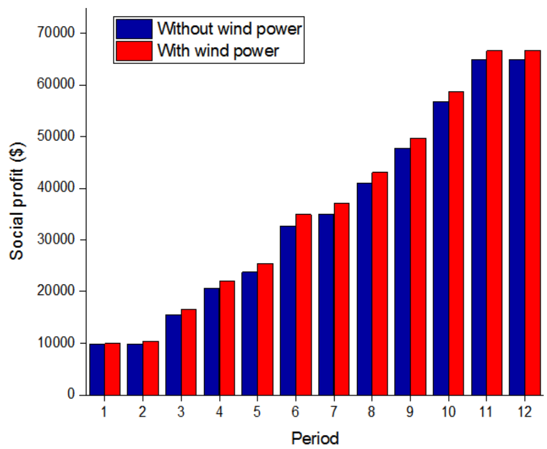

Fig.4. Social profit with and without wind power for 12 period

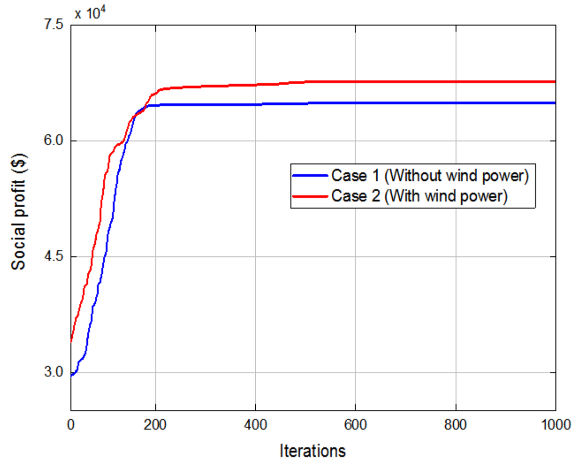

Fig.5. Social profit convergence characteristics

Table 8. Social profit and generation cost comparison

Case	Total Generation cost ($)	Total Social profit ($)
Without wind power	492362.90	422425.90
With wind power	473736.17	441052.57
Improvement by wind integration	18626.73	18626.67

Table 6 shows that if the wind generator is operating at 100%, the total generation cost after the 12-trading period is minimized from 492362.90 $ to 473736.17 $, saving $18626.73 and improving the total social profit, which was maximized from $422425.90 to $441052.57 with $18626.67 during the 12-trading period. It is concluded that the bid-based dispatch solution using the proposed SA algorithm with wind power succeeds in reducing the energy produced and the total generation cost of thermal units leading to a maximal social profit for market participants.

The convergence characteristic of the proposed SA algorithm to solve the BBDED problem with and without wind power is shown in Fig. 5.

Conclusion

In this paper, the BBDED problem is solved using the SA algorithm, which was tested on a 10-units test system. In the first part of this study, the objective of determining the economic generation and demand level of GENCOs and customers is carried out to achieve a maximum social profit in the electricity market while satisfying all operating constraints during trading periods. In the second part, the wind power integration impact is studied in the dispatch model, particularly on generation cost and social profit. The comparison was made between bid-based dispatch without and with wind power. The bid-based dispatch with wind energy has shown better performance in minimizing generation cost, which has led to maximizing the social profit of the participants' after-market clearing, confirming the advantages of renewable energy in power systems. The simulation results have proven the optimality and efficiency in the convergence of the prosed SA method compared to other methods to solve the BBDED problem. Future work will include the study of the emission constraint and the integration of FACT devices to improve the system's stability when integrating renewable energy into the BBDED problem.

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