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Artificial bee colony algorithm applied to optimal power flow solution incorporating stochastic wind power

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ABSTRACT

This paper focuses on the artificial bee colony (ABC) algorithm, which is a nonlinear optimization problem. is proposed to find the optimal power flow (OPF). To solve this problem, we will apply the ABC algorithm to a power system incorporating wind power. The proposed approach is applied on a standard IEEE-30 system with wind farms located on different buses and with different penetration levels to show the impact of wind farms on the system in order to obtain the optimal settings of control variables of the OPF problem. Based on technical results obtained, the ABC algorithm is shown to achieve a lower cost and losses than the other methods applied, while incorporating wind power into the system, high performance would be gained.

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1. INTRODUCTION

The majority of the world's fossil-fuel power generation operations use coal and natural gas to generate electricity, which is one of the most expensive commodities used to generate electric power. Polluting emissions from electricity generation based on the combustion of fossil fuels account for a sizable portion of global greenhouse gas emissions [1], [2]. As a result of economic and environmental reasons, workers in the field of electric energy were encouraged to increase and develop renewable energy. The electrical power control are experiencing noteworthy changes due to an increase in wind energy penetration level, causing unused challenges to system operation and planning [3], [4]. Therefore, the operators of power systems both in the planning and operating stage are very interested in optimal power flow (OPF) [5]. The main objective of an optimal power flow methodology is to find the ideal working of a power system by optimizing a specific objective whereas fulfilling certain indicated physical and security limitations [6], [7].

In recent years, the rapid development of computational intelligence have motivated researchers in the field of optimization algorithms to resolve various complex optimization cases such as particle swarm optimization algorithm (PSO) [8], [9], improved colliding bodies optimization method [10], imperialist competitive method [11], black-hole-based optimization technique [12], differential evolutionary technique [13], hybrid algorithm of PSO and GSA algorithms [14], gravitational search method (GSM) [15], [16], improved PSO algorithm [17], biogeography-based optimization technique [18], chaotic self-adaptive differential harmony search method [19], grey wolf optimizer [20], fuzzy-based hybrid PSO algorithm [21], differential search technique [22], multiphase search optimization technique [23], harmony search technique

[24], Jaya optimization technique [25], artificial bee colony (ABC) algorithm [26], differential evolution (DE) [27], biogeography-based optimization (BBO) [28], teaching-learning-optimization algorithm [29], and the firefly algorithm (FA) [30]. This paper was motivated by two factors. First, the application of the artificial bee colony algorithm to solve the optimum power flow problem has been studied. Second, solving OPF considering wind power penetration of different sites (single & multiple) and studying the impact of the wind power penetration on the slack bus generation, the total production cost, active power losses and voltage deviation.

2. OPF PROBLEM FORMULATION

The solution to the OPF problem involves the optimization of objective function and obtaining the optimal settings of the power system control variables. The formal OPF problem can be written as [31]:

$$Min.\, \mathrm{F}\,(\mathrm{x}, \mathrm{u}\,) \tag{1}$$

Subject to

$$\mathrm{g}\,(\mathrm{x}, \mathrm{u}\,) = 0 \tag{2}$$

$$\mathrm{h}\,(\mathrm{x}, \mathrm{u}\,) \leq 0 \tag{3}$$

Where F refers to the target (objective) function to be minimized, x and u are state and control variables respectively. The state vector x including; i) P_{G1}, generating power at swing (slack) bus, ii) Q_G, reactive generating power outputs, and iii) V_L, load bus voltage. x can be written as:

$$\mathrm{xT} = [\, P_{G_1}, Q_{G_1} \ldots . Q_{G_{NG}}, \mathrm{S1} \ldots . S_{L_{NTL}}\, V_{L_{L1}} \ldots . V_{L_{NL}}\,] \tag{4}$$

Where NG, NL, NTL and SL are the number of generator buses, number of load buses, transmission lines and number of transmission line loading, respectively. The control vector u including; i) P_G, generator active power outputs, ii) V_G, generator voltages, iii) Q_C, shunt VAR compensations, and iv) T transformer tap settings. u can be written as:

$$\mathrm{uT} = [\, P_{G_2}, \ldots . P_{G_N}, V_{G_1} \ldots . V_{G_{NG}}, \mathrm{Qc1}, \ldots ., Q_{C_{NC}}, \mathrm{T1} \ldots . \mathrm{T_{NT}}\,] \tag{5}$$

Where N_C and N_T are the shunt VAR compensators output and the transformers regulated number, respectively [31].

2.1. OPF objective functions

Two different objective functions are chosen in the current paper. The 1st is the economic objective whereas the 2nd is the technical objective.

2.1.1. Economic objective

The main objective of the optimization problem is minimizing the operating costs in the wind-thermal power system.

a. Cost model of thermal power generators

Consider f_i as a generator fuel cost, given as in (6) [25], [32]:

$$f_1 = \sum_{i=1}^{NG} (\, a_i + b_i P_i + c_i P_i^2\,)\ (\$/\mathrm{hr}) \tag{6}$$

Where a_i , b_i , c_i cost coefficients of fuel generators i^{th}, N number of generation units, P_i active power generation of generators i^{th}.

b. Cost model of wind power turbines

The goal of the current paper's optimization problem is to minimize the overestimated and underestimated costs of wind energy caused by wind speed uncertainty. According to:

$$f\,2 = \sum_{j=1}^{m} WPCost_{ue,j} + WPCost_{dir,j} + WPCost_{oe,j} \tag{7}$$

Where $WPCost_{ue,j}$ is underestimation scaled average cost for wind power in $/MW h, $WPCost_{dir,j}$ is directly cost output wind power and $WPCost_{oe,j}$ is overestimation scaled average cost for wind power in MW. $WPCost_{dir}$ be written as:

$$WPCostdir \ = \ \sum_{j=1}^{m}(w_j \times q_j) \tag{8}$$

Where w_j is active power generated by j_{th} wind turbine and q_j is direct cost coefficient.

$$WPCostoe\ ,j \ = \ \sum_{j=1}^{m}(\ qC_{rwj} \ \times E(\ Y_{oe.j}\ )) \tag{9}$$

E(Y_(oe.j)) can be written as:

$$E(\ Y_{oe.j}\ ) \ = \ w_j\ 1 \ - \ exp\ (-\ \frac{v_{in.j}^{k_j}}{C_j^{k_j}}) \ + \ exp\ (-\ \frac{v_{out.j}^{k_j}}{C_j^{k_j}}) \ + \ (\ \frac{w_{r.j}\, v_{in.j}}{v_{r.j}\, v_{in.j}} \ + \ w_j\ ) \ exp\ (-\ \frac{v_{in.j}^{k_j}}{C_j^{k_j}}) \\ - exp\ (-\ \frac{v_{1.j}^{k_j}}{C_j^{k_j}}) + (\frac{w_{r.j}\, C_j}{v_{r.j} - v_{in.j}})\ \Gamma\ (\ 1 + \frac{1}{k_j}\ ,(\frac{v_{1.j}}{C_j})^{k.j}\ ) - \Gamma\ (\ 1 + \frac{1}{k_j}\ ,(\frac{v_{in.j}}{C_j})^{k.j}\ ) \tag{10}$$

and

$$WPCostue\ ,j \ = \ \sum_{j=1}^{m}(\ C_{pwj} \ \times E(\ Y_{ue.j}\ )) \tag{11}$$

E(Y_(ue.j)) can be written as:

$$(\ Y_{ue.j}\ ) = w_{r.j} - \ w_j\ exp\ (-\ \frac{v_{r.j}^{k_j}}{C_j^{k_j}}) - exp\ (-\ \frac{v_{out.j}^{k_j}}{C_j^{k_j}})\ (\frac{w_{r.j}\, v_{in.j}}{v_{r.j}\, v_{in.j}} + w_j\ )\ exp\ (-\ \frac{v_{r.j}^{k_j}}{C_j^{k_j}}) \\ - exp\ (-\ \frac{v_{1.j}^{k_j}}{C_j^{k_j}}) + (\frac{w_{r.j}\, C_j}{v_{r.j} - v_{in.j}})\ \Gamma\ (\ 1 + \frac{1}{k_j}\ ,(\frac{v_{1.j}}{C_j})^{k.j}\ ) - \Gamma\ (\ 1 + \frac{1}{k_j}\ ,(\frac{v_{r.j}}{C_j})^{k.j}\ ) \tag{12}$$

Where Cpwj and Crwj are the overestimation and underestimation cost coefficient of jth wind generator in $/MW h respectively. $E\big(\ Y_{oe.j}\ \big)$ and $E(\ Y_{ue.j}\ )$ are the overestimation and underestimation anticipated value of wind power for jth wind turbine. kj and cj are a shape factor and a scale of the jth wind generator respectively estimating of wind speed in the Weibull probability density function (pdf). v_{inj}, $v_{out,I}$, $v_{r,j}$ are cut-in, cut-out and rated wind speed respectively. $v_1 = v_{in} + (v_r - v_{in})\ w_1/w_r$ is an intermediary parameter in [6]. Minimize the total production cost in wind-thermal power system can be expressed as [33]:

$$Min.C \ = \ f1 \ + \ f2 \tag{13}$$

2.1.2. Technical objective

In this paper, two objective functions are considered for the technical category. First, minimize the total active power losses which can be expressed as:

$$\mathrm{PL} = \ \sum_{k=1}^{m} G_K\ (\ V_i^2 + \ V_j^2 2V_iV_j \cos\big(\delta_i - \ \delta_j\big)\ ) \tag{14}$$

Where m is the total number of lines in the system, G_k is the conductance of the k_{th} line, V_j and V_i are the voltage magnitude at bus j and bus i respectively, δ_j and δ_i are the voltage phase angle at bus j and i respectively [34]. Second, minimize the voltage deviation (VD) of all load buses to improve the voltage profile on load buses. The voltage deviation given by (15) [35]:

$$\Delta \mathrm{V} = \ \sum_{\mathrm{k=1}}^{\mathrm{N_{PQ}}} |\ \mathrm{V_K} - \ \mathrm{V_K^{des}}| \tag{15}$$

3. OVERVIEW ON ARTIFICIAL BEE COLONY ALGORITHM

In 2005, Dervis Karaboga proposed a new optimization technique that is the artificial bee colony (ABC) algorithm. The ABC algorithm has been shaped by closely watching the exercises and actions of genuine bees while they were looking for nectar assets and sharing the sum of the assets with other colony

members. The colony of artificial bees consists of three main groups, which are the employed bees, onlooker bees and scout bees. This breed of bee features a distinctive part within the optimization preparation. The employed bee can remember the location of the extra nectar as well as it chooses the best of the others to drink from, while the onlooker bees use what the employed bees have collected to come up with a solution for what nectar they can't remember. For an optimization problem, an algorithm consists of three steps is as follows: In the first step, the employed bees are dispatched to find all the resources needed, and then the nectar amount is calculated. Step two, the onlooker bees choose an asset that matches the information from the already-discovered honeydew assets. The employed bumblebee was sent out to the fields to select new locations in order to identify potential food sources. "Looking" bees would be further broken into two categories: the "used" bees and the "observing" bees. The algorithm works on the basis that the number of employable bees equals the number of available sources of nectar. When we understand where the issues likely lie, we'll be better equipped to deal with them [36].
ABC algorithm:

a) Initialization phase

In the first step, variables xi (i = 1, 2, 3, … S) that have not been measured yet are selected at random, using some sort of random methodology.

b) Employed bee phase

The new sources are identified by each employed bee whose amounts are equal to the half of the total sources. a new source can be found by:

$$V_{ij} = X_{ij} + \varphi_{ij}(X_{ij} - X_{kj}) \tag{16}$$

Where j is a randomly selected parameter index, k is a random number between [0, 1] and it has to be different from i, φ_{ij} is a random number within the range [-1, 1], X_{ij} is the current position of food source which comparing two food postion visually by bee from this parameter the production of the neighbor food source can be controlled. The new food source postion V_{ij} is produced and evaluated by the artificial bee,by comparing the current food source with previous source taking its performance in the consider. From the information that obtained if the new source has equal or better amount of food or nectar than the old source,it used to replace the old source in the memory. Otherwise, the old source would be retained in memory.

c) Onlooker bee phase

In this phase ,the onlooker bees are work on the principle of probability by selecting the food source with probability can be written as:

$$P_i = \frac{f_i t_i}{\sum_{j=1}^{S_N} f_i t_j} \tag{17}$$

Where $f_i t_i$ and P_i are the fitness value and probability associated with solution i respectively. In each colony, great responsibility for random research is scout bees' bear.

d) Scout bee phase

In this stage, the scout bee randomly investigates food sources without direction from the queen. Every scout in the swarm thinks that he or she is an explorer. If the supply of food decreases below the gainful level or as a result of applying a given level of the food application of the nectar, the bees associated with it cease feeding. When you have new information, a new understanding, or a new insight, the limit on the number of bees tells you how many from the source and how many to the destination.

$$X_{i,j} = X_{min,j} + \text{rand}\,(0,1) * (X_{max,j} - X_{min,j}) \tag{18}$$

Where $X_{max,j}$and $X_{min,j}$ are the maximum and minimum limits for optimization parameter, rand (0, 1) is a random number within the range [0, 1]. The number of iterations in ABC algorithm considered as the important criterion for stopping an ABC algorithm.

An optimization algorithm might therefore determine that the stopping criteria to be:

1. Number of maximum iterations
2. Maximum error between two consecutive iterations

Figure 1 shown the flowchart of the ABC algorithm based OPF problem.

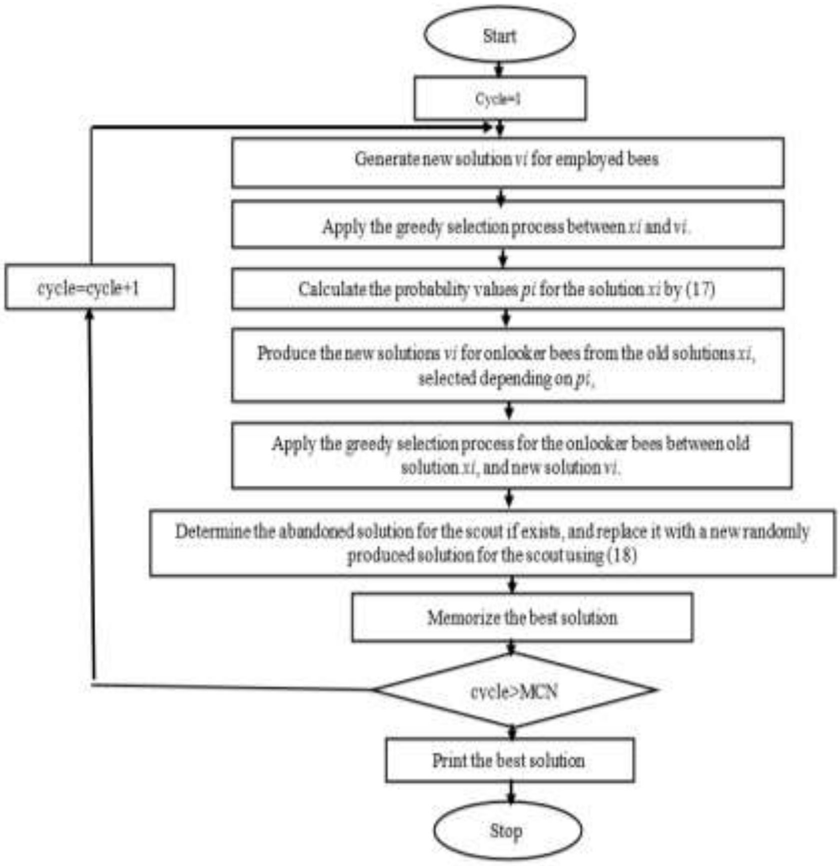

Figure 1. The flowchart of ABC based on OPF problem [37]

4. CASE STUDY

In this paper, two wind farms connecting to bus 10 and bus 24 are suggested. Figure 2 shown the standard IEEE 30 system with two wind farms. The wind power penetration level is defined as the ratio of the installed wind power capacity to the total-installed system generation capacity of 10%. The total power generation of six thermal generating in system are around 400MW, therefore the installed wind power capacity is 40 MW. Two wind farms included 10 wind turbines each one has rating 2 MW (Vestas V90, 2 MW) and connected at bus 10 and bus 24 (20 MW in each bus) is used to analyse the impact of incorporating wind farm on different performance analysis of system. Several scenarios with dispersed wind penetration levels from 0% to 100% have been investigated.

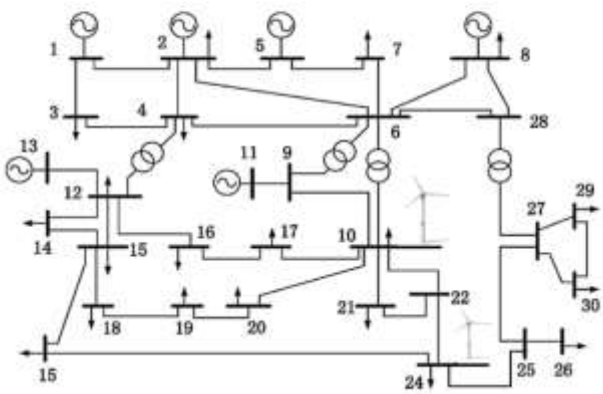

Figure 2. Single-line diagram of the IEEE 30-bus system including two wind farms at bus10 & bus 24

4.1. OPF without incorporating wind power

In this case, they used the artificial bee colony (ABC) algorithm to find a solution for OPF that did not include a wind farm. The power generation in thermal generator, active power loss and total production cost obtained by ABC algorithm is compared with other methods obtained in the [34]. Table 1 shows the results of this comparison. An 800.638 $/hr total production cost has been obtained by ABC, which is better than linear programming (LP) in [34].

Table 1. Comparison of ABC with LP for IEEE 30-bus system

Variable	ABC	LP [33]
Pg1(MW)	177.05	195.6439
Pg2(MW)	49.76	43.8668
Pg5(MW)	21.38	21.4574
Pg8(MW)	20.76	10.5771
Pg11(MW)	11.63	10.0866
Pg13(MW)	12	12.0000
Power Loss (MW)	8.9246	10.31
Production cost ($/hr)	800.6380	803.26

4.2. OPF incorporating single wind farm site

In this case, the wind farm is incorporated on bus 10 and bus 24 separately (20 MW in each bus), for penetration levels from 25% to 100% with an interval of 25. The comparison results between ABC and the results obtained in the [34] for slack bus generation, total production cost, active power losses and voltage deviation are shown in Table 2. Figure 3 shows the load bus voltage profiles and Figure 4 shows the convergence characteristic of total production cost for this case when the wind farm is incorporated at bus 10.

Table 2. Comparison of ABC with LP when wind farm with different wind power penetration levels connected to system

Wind penetration	Bus no.	ABC				LP [33]			
		slack bus	Cost($hr)	Losses (MW)	VD (p.u.)	slack bus	Cost($hr)	Losses (MW)	VD (p.u.)
0%	10	177.05	800.638	8.9246	0.8977	176	802.46	10.31	0.8513
25%		171.38	783.142	9.152	0.604	175	791.03	9.12	0.594
50%		166.01	765.221	8.246	0.920	171	776.83	9.05	0.900
75%		160.65	747.941	7.888	0.931	166	764.63	8.79	0.912
100%		155.31	730.943	7.550	0.941	160	753.42	8.27	0.930
0%	24	177.05	800.638	8.9246	0.8977	176	802.46	10.31	0.8513
25%		171.28	782.447	8.522	0.924	177	790.89	9.03	0.900
50%		165.83	764.657	8.072	0.948	172	776	8.85	0.915
75%		160.43	746.814	7.674	0.972	168	764.63	8.34	0.960
100%		155.09	730.234	7.326	0.993	163	753.42	7.96	0.984

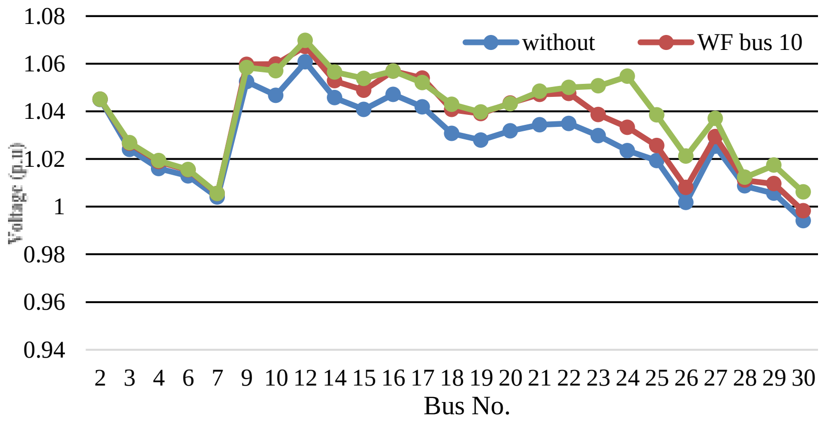

Figure 3. Load bus voltage profile 30-bus IEEE system

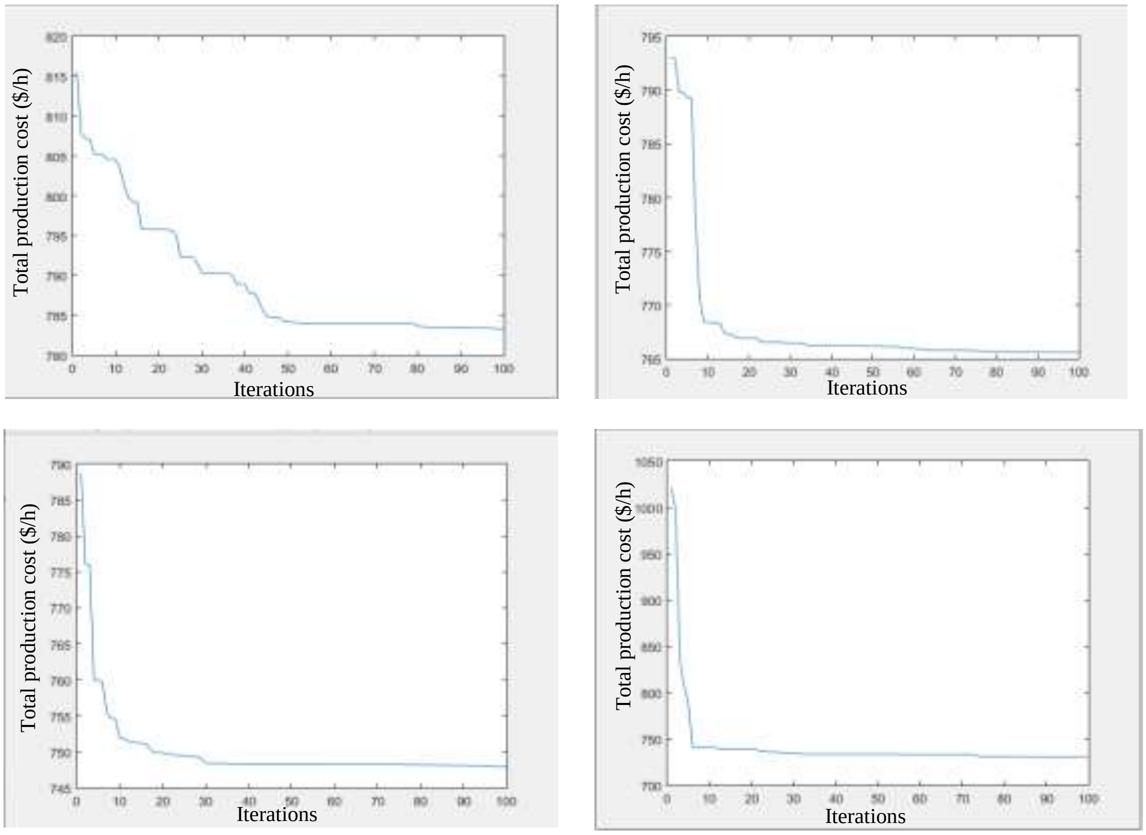

Figure 4. Convergence characteristics of the ABC for penetration levels of wind power at bus 10 only

4.3. OPF incorporating multiple wind farm

This case shows the impact of incorporating a wind farm connected to bus 10 and bus 24 together (20 MW in each bus). For penetration levels from 25% to 100% with an interval of 25%. Table 3 shows the slack bus generation, the total production cost, active power losses and voltage deviation. Figure 5 shows the load bus voltage profiles and Figure 6 shows the convergence characteristic of total production cost for this case.

Table 3. Comparison of ABC with LP when wind farm with different wind power penetration levels connected to system

Wind penetration	Bus no.	ABC				LP [33]			
		slack bus	Cost($hr)	Losses (MW)	VD (p.u.)	slack bus	Cost($hr)	Losses (MW)	VD (p.u.)
0%	10	177.05	800.6380	8.9246	0.8977	176	802.46	10.31	0.8513
25%	&	165.90	764.670	8.614	0.639	170	758.89	9.03	0.602
50%	24	155.12	730.526	8.502	0.643	159	736.91	8.85	0.609
75%		144.44	694.795	7.599	0.905	148	701.78	8.34	0.885
100%		133.86	661.621	7.565	0.813	138	680.59	7.96	0.803

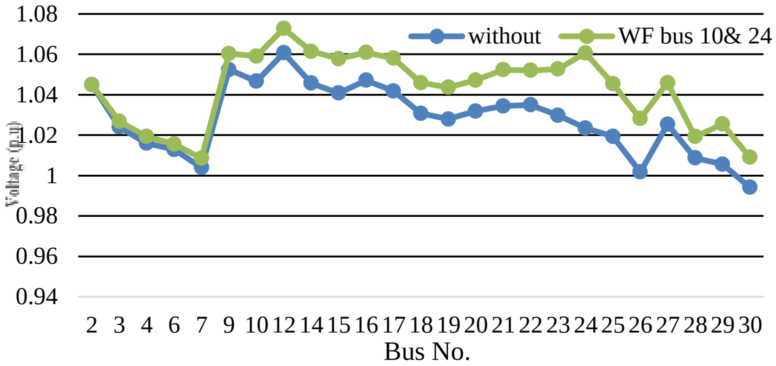

Figure 5. Load bus voltage profile 30-bus IEEE test system

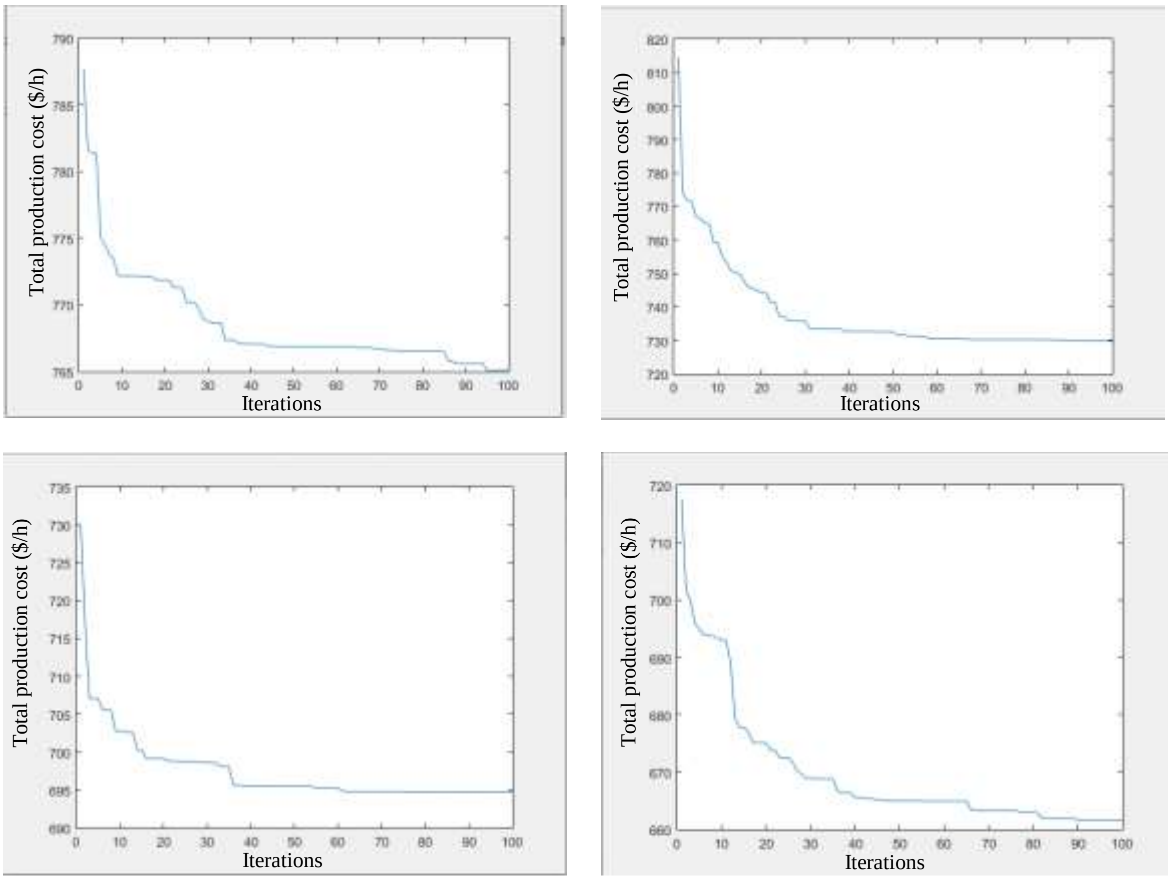

Figure 6. Convergence characteristics of the ABC for penetration levels of wind power on bus 10 & 24 together

5. CONCLUSION

This paper proposes the application of artificial bee colony (ABC) algorithm optimal power flow for a system that incorporates thermal units and wind farms during normal operation. The performance of the ABC was applied to standard IEEE-30 bus system with and without incorporating wind farm to show its impact on the the slack bus generation, the total production cost, active power losses and voltage deviation, and compared its simulation results with another method. Based on technical results obtained are it can be noticed that the ABC high performance than the rest methods, and concluded that an optimal integration and location of wind farms give significant to system, such as reducing in the total production cost, active power losses and improvement in the load bus voltage profile, while high performance can be noticed when a wind farm site on bus 24 rather than its site on bus 10. Finally, the results are exceptionally much promising.

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