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Optimal Power Flow Considering Wind Integration using Anti lion Optimization Algorithm

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ABSTRACT
Optimal Power Flow (OPF) is one of the major power system planning and operation problem. It is used to minimize the generation cost and power losses while maintaining the power system stability. It is considered as a complex optimization problem which includes linear, non-linear and large-scale constraints. This problem is essential to obtain the objectives while maintaining constraints. Moreover, as wind power growth, the power systems are facing challenges for operating and control to maintain the stability and continuity. This paper focuses on applying the OPF considering wind energy resources. A recent metaheuristic algorithm called ant lion optimizer (ALO) is used to solve the OPF problem. The OPF objective considers parameters such as minimizing the operating cost, minimizing the power losses, minimizing the wind power curtailment and improving the voltage profiles. It is subjected to power system and wind energy constraints. It is implemented by a MATLAB code for optimizing the parameters of the OPF. To evaluate the ALO performance in solving the OPF problem, a modified IEEE 30-bus system includes wind turbine generators is employed.
Keywords - Optimal Power Flow (OPF), Ant lion optimizer (ALO), Wind power, MATLAB.

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I. INTRODUCTION

Continuously increasing the demand for energy led to seek ways to integrate the renewable energy sources with the electric grids. Nowadays, many different renewable energy resources such as wind, solar, geothermal, tidal and biomass energy are available. The wind energy (WE) is one of the most available renewable energy resources in the world. But the irregular generation capacity is the main challenge with the integration of WE in the electric grids. It is characterized with variable out power due to of the stochastic nature of wind resources. Moreover, the construction of the wind turbines is very expensive and their noise pollution should be taken into considerations. Electrical networks (ENs) are generally complex, they consist of generation, transmission, and distribution system and the load demands. The Operational Engineers need a development tool obtain the solution of the power flow problems to minimize the operating costs and losses of the ENs. Additionally, connected the WE resource to the ENs are led to significant impacts on the planning and operation of the transmission system. This can cause over-loading in numerous transmission lines [1-3].

Optimal power flow (OPF) is considered as a vital tool in planning and operation of electrical power system. The OPF problem is formulated in single or multi-objectives that to minimize the power generation costs, voltage deviation and transmission line losses. under equality and inequality constraints. Moreover, The OPF problem can be formulated in two types; or static OPF [3].

The OPF methods can be classified to conventional and Artificial Intelligence (AI) methods. The conventional methods include; Gradient methods [4-5], Linear Programming (LP) [6-8], Quadratic Programming (QP) [9-11], Newton-Raphson (NR) [12-13], Non-linear Programming (NLP) [14-15], and Interior Point (IP) [16-17]. Gradient method is based on the first order derivative vector of the objective function (OF) to obtain the improved direction for the iterative steps of the solution. Ref. [4] used the gradient method to solve the problem of OPF problem, by applying a penalty technique to carry out the constraints and dependent variables in the acceptable limits. Ref. [5] improved the used method by adding penalized security variables were added to the OF. The LP method was used to determine the OPF [6]. The method was applied on Five-bus (220kV) system.

Ref. [7] applied the LP method to find the optimal locations in distribution network to install the capacitors while minimizing the power losses. In Ref. [8] the generator reactive limits and the losses of power were minimized based on the LP method. In each iteration, the OF and the constraints were linearized. The generalized Quadratic method was applied for solving the OPF [9]. The method used the sensitivity of the OF with optimally adjustments the constraints. Ref. [10] introduced an optimization model to the reactive power based on the successive QP method. Ref. [11] formulated the problem of economic dispatch as a QP problem then was solved by using the Wolfe's algorithm. NR method was applied to solve real time emission dispatch problem considering the sensitivity factors [12]. The NR method was modified to include the unified power flow controller (UPFC) [13]. A combined method of network flow programming and QP was applied to solve the multi-area economic dispatch problem [14]. Bothe the NLP and LP were used to solve the reactive OPF to locate the reactive power among the deregulated system and generators [15]. The IP based primal dual logarithmic was presented to solve the reactive power dispatch problem [14]. Ref. [15] solved the OPF problem by using the IP method for nonlinear programming. The most aforementioned methods are suffered from weak in dealing with qualitative constraints, required differentiability and linearization and poor convergence.

Recently, many intelligent optimization techniques were applied and adapted to solving many types of the multi objective OPF different in the OF and constraints [16-35]. The genetic algorithm (GA) was used to solve a large-scale economic dispatch [16]. The ramp-rate limits, network losses and prohibited zone’s avoidance were considered in solving the problem. Ref. [17] introduced a hybrid GA and Mat power to solve the OPF problem. Ref. [18] constructed the OPF problem as multi-objective optimization problem. The particle swarm optimization (PSO) was used to solve the conventional ED problem where the OF is a quadratic cost function and nondifferential region [19, 20]. The valve point effects were considered in [21]. The PSO-fuzzy and GA-fuzzy optimization were used to determine the OPF [22]. Artificial Bee colony (ABC) technique was used to solve the OPF problem [23]. It was tested by applying it on IEEE-14 and 30 bus system. Ref. [24] applied a modified ABC technique to solve the OPF problem containing continuous and discrete variables. The differential evaluation (DE) method was introduced in [25] to solve the OPF as a multi-objective problem to control the Pareto size. Ref. [26] applied a modified DE technique to solve the OPF problem with non-convex and smooth fuel cost of generators. The grey wolf optimizer (GWO) technique was used in [27] to solve the OPF problem. The line stability index was taken into consideration while solving the OPF problem. Moreover, the Pareto method was used to obtain the best point for the multi-objective function. An optimal reactive power dispatch problem was solved using GWO technique [28]. The shuffle frog leaping (SFL) technique was modified for solving the multi-objective OPF considering the emission constraint [29, 30]. The augmented Lagrangian relaxation method was used to solving the multi-area decentralized OPF in electrical power system [31].

Recently, the rate of the wind energy was increased in the electric networks, so the researchers were concerned about how to integrate a large penetration of non-dispatchable wind power generation without disrupting the power balance in the electric network. The OPF problem was solved considering the WE in [32]. the Weibull Distribution Function was used to model the alternatives of wind speed. Moreover, the guided artificial bee colony (GABC) method was used to obtain the OPF optimization problem solution. The Gravitational Search Algorithm (GSA) and the Moth Swarm Algorithm (MSA) were used as hybrid technique to obtain the solution of the OPF problem for power system connecting to WE source [33]. Ref. [34] presented a real-time (minute-to-minute) and day ahead (every 15 minutes) for OPF to obtain the optimum values of the control variables in the electric networks. Ref. [35] introduced a three level of adaptive robust OPF considering WE in the electric networks. Both the uncertainty of wind speed and demand were characterized.

II. WIND POWER GENERATION MODEL

The Weibull probability distribution functions, g(v), are used to describe the variation of wind speed characteristics with the scale factor, s, and shape factor, k. For any time period, the wind speed probability is given by [32];

$$g(v) = \left(\frac{k}{s}\right)\left(\frac{v}{s}\right)^{(k-1)} . e^{-(v-s)^k} \qquad 0 < v < \infty \tag{1}$$

where *s* and *k* are the scale and shape factors respectively. *v* is the wind speed m/s. The wind speed probability that will be equal or less than *v* is defined as the cumulative distribution function, *G(v)*. It can be expressed by the following equation;

$$G(v) = 1 - e^{-\left(\frac{v}{s}\right)^k} \tag{2}$$

The output power from the wind turbine, P_w, in watts can be calculated as a function of wind speed [36].

$$P_w = \begin{cases} 0 & v_{\text{cut-in}} \geq v \geq v_{\text{cut-off}} \\ 0.5\rho A C_p v^3 & v_{\text{cut-in}} \leq v \leq v_{rated} \\ P_w^r & v_r \leq V \leq v_{\text{cut-off}} \end{cases} \tag{3}$$

where P_w^r is the rated wind turbine power at rated wind speed or higher. ρ and A are the air density and wind turbine blade swept area, respectively. C_p is the power coefficient and equal 0.3. $v_{cut\text{-}in}$, $v_{cut\text{-}off}$ and v_r are the cut-in, cur-out and rated speed. Figure 1 illustrated the wind turbine output power curve.

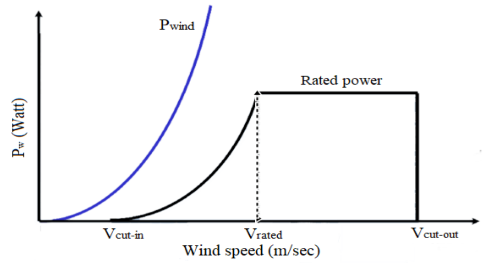

Fig. 1 Wind turbine output power curve

III. PROBLEM FORMULATION OF OPF

The OPF model is demonstrated in this section as a multi-objective optimization problem. OPF has an OF subject to some equality and inequality constraints. In this paper, it is proposed that, the OPF is a non-linear problem to reduce the cost by controlling the values of the control variables with respect some specific constraints.

3.1 Objective function

The objective of the OPF problem is to reduce the operation costs with satisfying the systems constraints. Thus, the proposed OF is constructed from cost functions; minimizing the generation cost of the fossil fuel generators, minimizing the wind power cost, minimizing the shortage of wind power expected reserve cost and finally, the cost of emissions. The total cost function can be represented as follows;

$$OF = C_1(P_g) + C_2(P_w) + C_3(P_w, P_{w,av}) + C_4(P_g) \tag{4}$$

where $C_1(P_g)$, $C_2(P_w)$, $C_3(P_w, P_{w,av})$ and $C_4(P_g)$ are the thermal generation units fuel cost, the cost of wind power generation, cost for not consuming the available wind power and cost of Carbon emission, respectively.

(i) Thermal generation fuel cost function

It can be defined by quadratic equation as illustrated in (5);

$$C_1(P_g) = \sum_{i=1}^{Ng} (\alpha_i + \beta_i\, P_{g,i} + \gamma_i\, P_{g,i}^2) \tag{5}$$

where N_g is the number of thermal generation units. $P_{g,i}$ is the active power produced from i^{th} unit. α_i, β_i, and γ_i are the constants of fuel cost of i^{th} unit.

(ii) Wind power cost

The WE cost is depended on the purchase agreement between the grid operators and the owners of the wind farms. It can be expressed by (6).

$$C_2(P_w) = \sum_{j=1}^{N_w} (cd_j . P_{w,j}) \tag{6}$$

where N_w is the number of wind turbines. $P_{w,j}$ represents the active power produced from j^{th} wind turbine and cd_j is the cost coefficient of j^{th} wind turbine.

(iii) Curtailed wind power cost

The under estimation of the wind power generated can cause wind power exceeds the precalculated value. So, some problems can be happened such as congestion in some transmission lines. This leads to power curtailment from the wind turbines during normal operation.

$$C_3(P_w, P_{w,av}) = \sum_{l=1}^{N_w} (P_{av,l} - P_{w,l}) \tag{7}$$

where $P_{av,l}$ is the available generated wind power of lth wind turbine. $P_{w,l}$ represents the active power produced from j^{th} wind turbine.

(iv) Emission cost

The emission cost is referred to minimizing the pollution of air produced from the thermal power plants. It represents by carbon penalization and can be expressed by;

$$C_4(P_g) = h \sum_{i=1}^{N_g} (a_i + b_i P_{g,i} + c_i P_{g,i}^2) \tag{8}$$

where a, b and c are the thermal generators emission coefficient and h is the value of carbon tax.

3.2 OPF problem constraints

The OPF problem constraints include balance of active and reactive power at any busbar, active and reactive generation power, voltage magnitudes at busbars, active power produced from wind turbines, limits of reactive output power of wind turbines, shunt reactive power injections, and lines flow limits.

(i) Active and reactive power balance

The balance equation of the active and reactive power is represented by (9) and (10);

$$P_{g,i} - P_{L,i} = \sum_{j=1}^{N_b} (|V_i||V_j|(G_{ij}\cos(\delta_{ij}) + B_{ij}\sin(\delta_{ij}))\quad i \in N_b \tag{9}$$

$$Q_{g,i} - Q_{L,i} = \sum_{j=1}^{N_b} (|V_i||V_j|(G_{ij}\sin(\delta_{ij}) - B_{ij}\cos(\delta_{ij}))\quad i \in N_b \tag{10}$$

where $P_{L,i}$ and $Q_{L,i}$ are bus i^{th} active and reactive loads and N_b is the total number of busbars. $|V_i|$ and $|V_j|$ are voltage magnitudes at bus i^{th} and j^{th}, respectively. B_{ij} and G_{ij} are the susceptance and conductance of transmission line connected between bus i^{th} and bus j^{th}.

(ii) Active and reactive generation power limits

The active and reactive generation power from the generators and wind turbines, should be limited within their lower and upper values.

$$P_{g,i}^{min} \le P_{g,i} \le P_{gi}^{max} \quad i = 1, 2, \ldots, N_g \tag{11}$$

$$Q_{g,i}^{min} \le Q_{g,i} \le Q_{g,i}^{max} \quad i = 1,2, \ldots, N_g \tag{12}$$

$$0 \le P_{w,i} \le P_{w,i}^{max} \quad i = 1,2, \ldots, N_w \tag{13}$$

$$-[(S_{w,i})^2 - (P_{w,i})^2] \le Q_{w,i}{}^2 \le [(S_{w,i})^2 - (P_{w,i})^2] \quad i = 1,2, \ldots, N_w \tag{14}$$

where $S_{w,i}$ and $Q_{w,i}$ are the apparent and reactive power of the wind turbine.

(iii) Buses voltage limits

The voltage magnitudes of buses should be restricted within their limitations as follows:

$$|V_i^{min}| \le |V_i| \le |V_i^{max}| \quad i = 1,2, \ldots, N_b \tag{15}$$

(iv) Transmission lines flow limits

The maximum power flow constraints for transmission lines are included into the OPF problem by (16).

$$|S_{ij}| \le S_{ij}^{max} \tag{16}$$

where S_{ij} is the flow apparent power and S_{ij}^{max} is the limit of line flow in line between bus i^{th} and j^{th}.

(v) Reactive power injection constraint

The capability of reactive power compensation which can be provided by shunt VAR compensator is restricted by their maximum and minimum limits as illustrated by (17).

$$Q_{c,i}^{min} \le Q_{c,i} \le Q_{c,i}^{max} \quad i \in N_c \tag{17}$$

where $Q_{c,i}$ is the reactive power injected to bus i^{th}, Nc is the number of shunt capacitor bus. $Q_{c,i}{}^{max}$ and $Q_{c,i}{}^{min}$ are the maximum and minimum value of injected reactive power.

IV. PROPOSED ANT LION OPTIMIZER ALGORITHM

The ALO technique is considered as one of the most fertile, reliable and robust optimization techniques. It is deduced from mimic the behavior of the ant-lion bug for hunting the pry. The ant-lion life cycle contains two stages. First stage is the larvae; the most life of ant-lion is occurred in larvae and is taken for hunting. While the second stage is the adult period, which is taken for reproduction [34-35]. The larvae dig a conical shape trap in the sand by moving over a circular path and throwing the sand with their shovel-shape head. After digging the trap, the larvae buried themselves under the sand in the center of the trap and waited for the ants or other prey to be trapped in the hole [36]. Ants fall into the trap due to the steep slope of their sides and their sharp edge. When the ant falls into the hole, it tries to climb over the walls of the hole to escape from it. Antlion tries to catch it by wiping sand toward the bottom of the hole and trying to bite it. After the ant has pulled and eats it, Antlions tosses food scraps and sand out of the hole and prepares the trap for the next hunting.

In this paper, the ALO is implemented to solve the OPF problem with connecting wind turbines. First the data of the test system (thermal generations units, transmission lines, loads, and wind power) is read. Second, the ALO parameters and the population are initialized. Third, the objective function is determined for every ant and antlion then assign the fitness value. While the number of iterations is less than the maximum number of iterations, update the antlion position by updating c and d parameters using the roulette wheel. Then the fitness of the ants is calculated and replace the antlion with the corresponding ant. Finally update the elite if the antlion becomes fitter than the elite. The flowchart of the proposed ALO algorithm is illustrated in Fig. 2.

V. TEST SYSTEM

The IEEE 30-bus system as shown in Fig. 3 is modified for testing the proposed ALO algorithm for solving the OPF problem including wind power sources. This system consists of thirty buses; six thermal generator units at buses 1, 2, 5, 8, 11, and 13. There are forty-one transmission lines, and four transformers with off-nominal tap ratio in line 6-9, 6-10, 4-12, and 28-27 as illustrated in Table 1. For the state variables such as voltages at load buses, the limits are between 0.95 and 1.1p.u. Table. 2 illustrates the generators data and their cost coefficients.

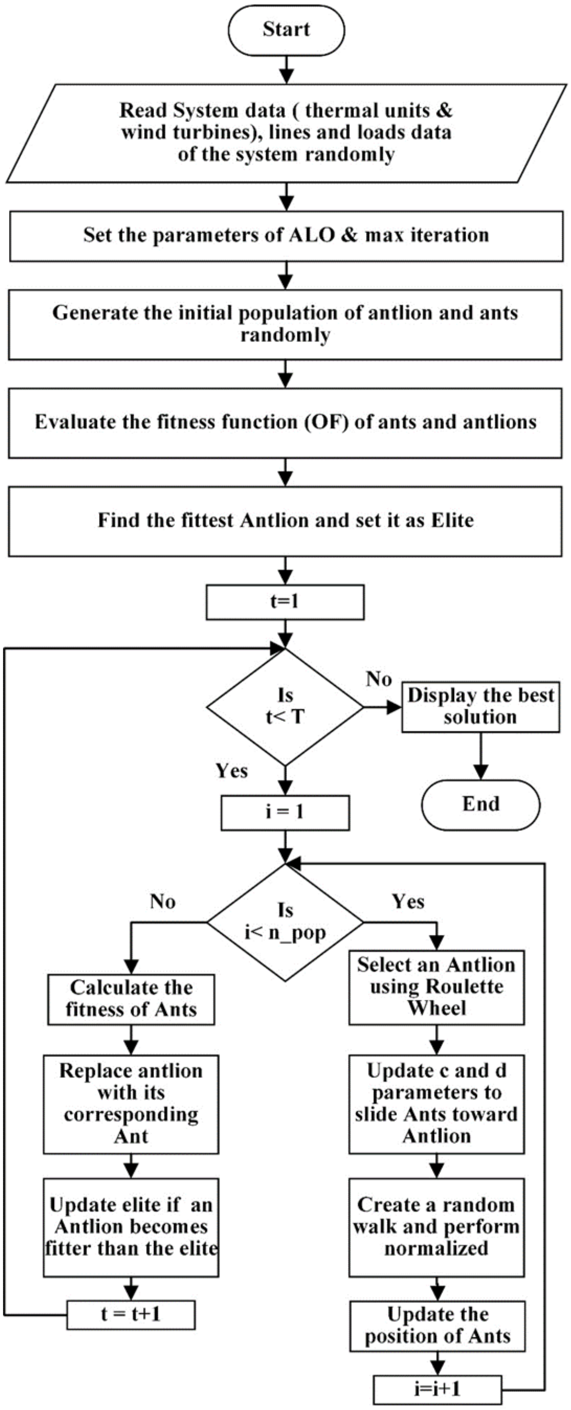

Fig. 2 proposed ALO algorithm Flow chart

Table. 1 Transformers off nominal tap settings

From Bus	To Bus	Tap setting Voltage (Pu)
6	9	0.978
9	10	0.969
4	12	0.932
28	27	0.968

Table. 2 Generator data and cost coefficients

Bus No.	P_g^{min}	P_g^{max}	Q_g^{min}	Q_g^{max}	Cost Coefficients		
					α	β	γ
1	50	200	-20	200	0	2	0.00375
2	20	80	-20	100	0	1.75	0.0175
5	15	50	-15	80	0	1	0.0625
8	10	35	-15	60	0	3.25	0.00834
11	10	30	-10	50	0	3	0.025
13	12	40	-15	60	0	3	0.025

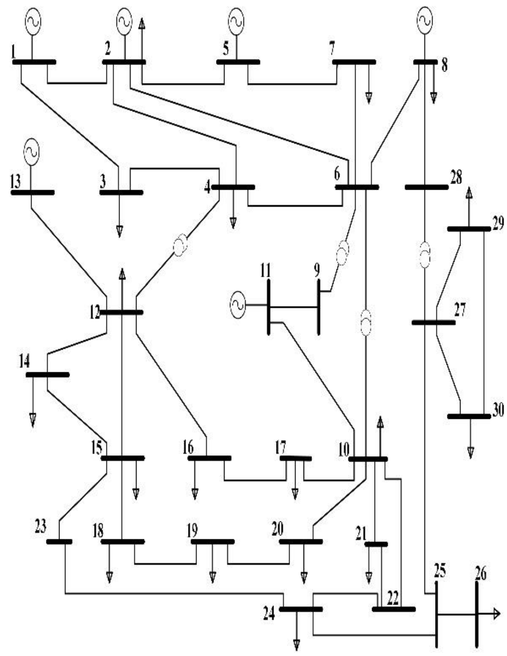

Fig. 3 Single line diagram of IEEE 30-bus system

VI. RESULTS AND DISCUSSIONS

To verify the efficiency and effectiveness of the proposed ALO method based OPF, two case studies are performed on the test system (Modified IEEE 30-bus system). First case, perform the OPF without connecting the wind turbines for different objective functions. Second case, the wind turbines are connected and the ALO-based OPF algorithm are performed on the test system. For all cases, the tolerance is selected to be 10^{-4} p.u. The proposed ALO-based OPF is executed by MATALB program.

6.1 Solution the OPF without connecting wind power

To perform this case, the OF in (4) is reduced by removing the terms of cost of WE generation. Only the fuel cost function is applied for this case. The generator and transmission data are illustrated in Tables 1 and 2. The optimum fuel cost determined from the proposed ALO-OPF method is compared with other optimization methods. As illustrated from Table. 3, the best fuel cost obtained from ALO-OPF method is 800.0463 ($/h) that is lower than that obtained from ABC and GSA algorithms [23, 33] reported in the literatures. Also, none of the compared algorithms satisfy all available mentioned technical constraints. Table. 3 demonstrates that; all the buses voltage magnitude values are within the limits. Moreover, the convergence curve of the ALO-OPF is illustrated in Fig. 4. The ALO method needs lower time to find the optimal solution than the other two methods.

Table.3 OPF without considering WE.

Control variables	**ALO**	**GSA**	**ABC**
P_{g1}	177.37	176.46	175.89
P_{g2}	48.68	48.86	48.86
P_{g5}	21.37	21.76	21.64
P_{g8}	21.2	21.43	22.4
P_{g11}	11.91	12.16	12.41
P_{g13}	12	12	12
$\|V_1\|$	1.089	1.0701	1.0433
$\|V_2\|$	1.068	1.0568	1.0235
$\|V_5\|$	1.035	1.0641	1.0021
$\|V_8\|$	1.067	1.041	1.015
$\|V_{11}\|$	1.053	1.032	1.0324
$\|V_{13}\|$	1.051	1.051	1.002
T_{11}	1.031	1.0132	1.0401
T_{12}	0.95	0.93	0.93
T_{13}	0.971	1.001	0.961
T_{14}	0.981	0.983	0.977
Fuel cost ($/h)	800.0463	801.5821	803.5785
Power loss (MW)	8.934	9.27	9.78

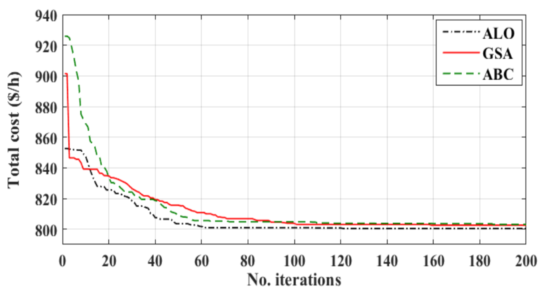

Fig. 4. Convergence curve for the optimization techniques

By taking into consideration the minimization of the fuel cost and the emissions, the proposed ALO-OPF method is applied on the test system and the results is compared with the other optimization methods, GSA and GABC. Table. 4 illustrates the results of OPF considering the fuel and emission costs. The total cost that obtained by the ALO is lower than that obtained by GABC and GSA. Also, the ALO is able to reach the minimum value of the OF faster than the two other methods as shown in Fig. 5.

Table. 4 Optimal power flow considering fuel and emission costs

Objective functions	**ALO**	**GABC**	**GSA**
Fuel cost ($/h)	828.939	830.012	834.3699
Emission (ton/h)	0.2545	0.2773	0.2492
P_{Loss} (MW)	6.271	6.0569	5.6825
Q_{Loss} (MW)	25.284	27.453	26.717
Total Cost	961.2905	970.526	971.453

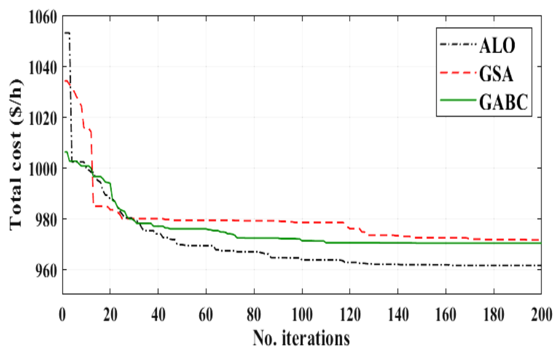

Fig. 5. Convergence curve for the optimization techniques

6.2 Solution of OPF considering wind power

In this case, the ALO-OPF algorithm is applied to the IEEE-30 bus integrated with the wind power in addition to the thermal generators. Three thermal generators are replaced by three wind turbines at buses 5, 11, and 13. The OF in this case is given by (4) that contains the wind power cost and the underestimated cost. Table. 5 illustrates the OPF results considering the WE.

Table 5 OPF considering WE

Control variables	ALO	GABC	GSA
P_{g1}	50.14	50.22	56.53
P_{g2}	20.28	20.58	34.285
P_{W5}	60	60	50.729
P_{g8}	34.56	35	65.956
P_{W11}	60	60	40.405
P_{W13}	60	59.999	39.162
$\|V_1\|$	1.0333	1.05431	1.043
$\|V_2\|$	1.0138	1.04764	1.0089
$\|V_5\|$	1.0236	1.033	1.0092
$\|V_8\|$	1.048	1.0437192	1.06
$\|V_{11}\|$	1.036	1.0801729	1.082
$\|V_{13}\|$	1.009	1.0776187	1.071
T_{11}	1.034	1.015	1.032
T_{12}	0.991	0.948	0.96
T_{13}	1.025	1.003	0.989
T_{14}	1.004	0.995	0.962
Fuel cost ($/h)	817.35	819.2931	864.13

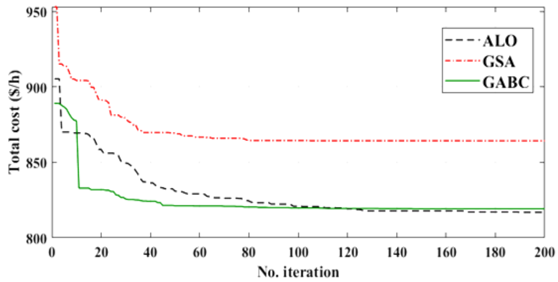

Fig. 6. Convergence curve for the optimization techniques

VII. CONCLUSION

A novel optimization algorithm has been applied in this paper to find the optimum solution of the OPF problem. It is applied for different objective functions; fuel cost, wind power cost, underestimation of wind power cost, and emission penalty cost. The proposed method (ALO) was compared with to evolutionary algorithms; GSA and GABC and ABC. From the results, the proposed optimization algorithm was able to find the optimum control variables for the OPF problem to satisfy the minimum cost and thus suitable for solving the non-smooth and complex problems.

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