AC Optimal Power Flow Problem Considering Wind Energy by an Improved Particle Swarm Optimization

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ABSTRACT:
This paper presents an AC Optimal Power flow (AC-OPF) problem of a power system, considering wind energy. Wind energy is an environmental-friendly energy source to produce electrical power and it includes less operating costs compared with other sources of electrical power production. Wind generators also affect the operation cost of a power system as well as transmission losses, based on generators locations and speed of wind. In addition, wind speed is a parameter with uncertainty and considering this uncertainty is an important issue in operation of wind generators in the AC-OPF problem. The proposed AC-OPF formulation includes the integer variables in addition to continuous variables and studies the effects of wind energy, transformer tap settings, and shunt capacitors on fuel cost, transmission losses as well as up and down spinning reserves. To solve the AC-OPF model, an Improved Particle Swarm Optimization (IPSO) is presented. The IPSO algorithm in this work includes velocity mirror effect that causes improvement in the quality of the results. The proposed method is applied on modified IEEE 30 bus test system, and obtained results approve the validity and effectiveness of the proposed method.

KEYWORDS: AC Optimal Power Flow, Wind Energy, IPSO, Velocity Mirror Effect.

1. INTRODUCTION

The Optimal Power Flow (OPF) was first presented by Carpentier in 1962 [1]. The target of OPF problem is finding the optimal objective function while constraints are satisfied. The objective function can be maximization of power quality, minimization of cost, power transfer capability, optimal voltage profile, load shedding, system load ability, etc. [2]. The most common objective is to minimize the generation cost or system losses. Recently, the AC Optimal Power Flow (AC-OPF) problem has been the most widely investigated as a nonlinear optimization problem, since it maintains system performance considering system constraints and limits such as active and reactive power limits, AC power flow limits (power balance), bus voltage, and line flow limits, etc. Traditional optimization methods to solve OPF and AC-OPF problem have been used in the past. Some of these traditional methods are Linear Programming (LP) [3-5], gradient method [6, 7], quadratic programming (QP) [8-10], non-linear programming (NLP) [11-13], interior point method (IPM) [14-16], etc. In spite of advancements in traditional methods, they suffer from the following drawbacks:

a) required linearization
b) required convexity
c) required differentiability
d) high chances to fall into local optimum
e) poor convergence
f) becomes slow if number of variables increases
g) to change the constraints or objective functions, it is required to have great number of changes [17]

Due to these drawbacks and using FACTS devices, the AC-OPF problem has been changed to a more complex one. Therefore, Artificial Intelligence (AI) methods, which can solve complicated and more detailed problems, have been emerged and developed to overcome defects of deterministic algorithms. Some of these techniques that have been widely used in OPF and AC-OPF problems are Genetic Algorithm (GA) [18-21], Particle Swarm Optimization (PSO) [22-26], Artificial Neural Network (ANN) [27, 28] , artificial bee colony (ABC) [29-31], Differential Evolution (DE) [32, 33], etc. As the AC-OPF problem is a complex optimization problem, some of the research works have neglected the

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uncertainty of wind and just considered deterministic models. Stochastic Programming (SP) is a tool for considering uncertainties in the OPF problem and ensures security of the system [34, 35].

Wind energy is an energy source to produce electrical power and its operating costs are less than other energy sources. While more Wind Generators (WG) are connected to power system utilities, the study of wind generators is becoming more necessary. Therefore, in this paper, the AC-OPF problem of the power system is solved by considering wind energy.

Moreover, the uncertainty of wind speed, the effects of shunt capacitors and transformer tap settings are considered in the AC-OPF model. However, a power system with WG must consider up spinning reserve and down spinning reserve. In addition, location of wind generators will affect both operations cost of power system and bus voltage as well as transmission losses. Thus, this paper presents a comprehensive formulation for the AC-OPF problem considering effects of wind generators on up and down spinning reserves, and the wind generation location's effect on transmission losses and fuel cost.

To solve this problem, a new solution method based on an Improved Particle Swarm Optimization (IPSO) is proposed. IPSO algorithm contains velocity mirror effect that improves the final results.

The remaining parts of the paper are organized as follows. Section 2 describes the optimal power flow formulation. Section 3 details the proposed IPSO algorithm. Section 4 declares simulation and numerical results. Finally, section 5 is the conclusion.

2. PROBLEM FORMULATION

AC-OPF problem is concerned with the steady state power system performance optimization associated with a multi-objective function while limited by various equality and inequality constraints. The Multi-Objective Function (MOF) of AC-OPF problem is to minimize the fuel costs of thermal units and transmission losses. The multi-objective function of this problem is as follows:

$$MOF: Min \quad FC + TL = \sum_{n=1}^{N_G} FC_n(P_n) + \sum_{l=1}^{B} TL_l \tag{1}$$

$$FC_n(P_n) = A_n.(P_n)^2 + B_n.P_n + C_n \tag{2}$$

$$TL_l = G_{ij}[|V_i|^2 + |V_j|^2 - 2|V_i||V_j| cos(\delta_i - \delta_j)] \tag{3}$$

Where, FC is the fuel cost; N_G is number of thermal units, P_n is generation of unit n; $A_n.B_n.C_n$ are coefficients of fuel cost function. TL is the transmission losses; B is number of branches; G_{ij} is conductance of the branch l between buses i and j; $|V_i|$ and $|V_j|$ are voltage magnitudes of buses i and j; δ_i and δ_j are voltage angles of buses i and j, respectively.

Voltage of P-V buses, P_n (generation of unit n), transformer tap, phase shifter angle and reactive power that is injected by shunt capacitors, are the control variables of equation (1). In this paper, it is assumed that there is not any cost of wind generators in the AC-OPF problem.

The constraints of the proposed AC-OPF problem can be presented as follows:

- Limits of active power:

$$P_{min}^n \le P_n \le P_{max}^n \quad ,n \in N_G \tag{4}$$

- limits of Reactive power:

$$Q_{min}^n \le Q_n \le Q_{max}^n \quad ,n \in N_G \tag{5}$$

- Nodal active/reactive power balance constraint for each bus $i \in I$ (AC power flow equations):

$$\sum_{n \in S_i^n} P_n + \sum_{w \in S_i^w} P(\mathrm{v}_w) - Pl_i - V_i \sum_{j=1}^{J} V_j \left(G_{ij} \cos(\delta_i - \delta_j) + B_{ij} \sin(\delta_i - \delta_j)\right) = 0 \tag{6}$$

$$\sum_{n \in S_i^n} Q_n - Ql_i - V_i \sum_{j=1}^{J} V_j \begin{pmatrix} G_{ij} \sin(\delta_i - \delta_j) \\ -B_{ij} \cos(\delta_i - \delta_j) \end{pmatrix} = 0 \tag{7}$$

Where, S_i^n is set of thermal units connected to bus i; S_i^w is set of wind generators connected to bus i; $P(v_w)$ is power output of wind generator; Pl_i and Ql_i are active and reactive load of bus i respectively and B_{ij} is susceptance of the branch l between buses i and j.

- Bus voltage limits

$$\mathrm{V}_{min}^k \le V^k \le \mathrm{V}_{max}^k \tag{8}$$

- Transformer tap setting limits

$$\Gamma_{nk}^{min} \le \Gamma_{nk} \le \Gamma_{nk}^{max} \tag{9}$$

- Limits for reactive power injection of capacitors

$$Q_{min}^C \le Q^C \le Q_{max}^C \tag{10}$$

- Transmission limit of branches

$$BF^l \le BF_{max}^l \tag{11}$$

- Limits of Phase shifter settings

$$\theta_{ik}^{phase\ min} \le \theta_{ik}^{phase} \le \theta_{ik}^{phase\ max} \tag{12}$$

- Spinning reserve constraints

$$\sum_{n=1}^{N_G} S_n^U \ge \sum_{i=1}^{I} Pl_i \times s\% + P_W \times r\% \tag{13}$$

$$S_n^U \le \min\left(\left(P_{\max}^n - P_n\right), \left(S_{\mathrm{U,max}}^n\right)\right) \quad n \in N_G \tag{14}$$

$$\sum_{n=1}^{N_G} S_n^D \geq P_W \times r\% \quad (15)$$

$$S_n^D \leq \min\left(\left(P_n - P_{\min}^n\right), \left(S_{D,\max}^n\right)\right) \; n \in N_G \quad (16)$$

Where, P_W is power output summation of all wind turbine generators $P(v_w)$; S_n^U and S_n^D are, up and down spinning reserve capacity contribution of thermal unit n; s% is percentage of active loads for up spinning reserve; r% is percentage of wind generation related to up and down spinning reserve; $S_{U,max}^n$ is maximum response rate constrained up spinning reserve related to thermal unit n; $S_{D,max}^n$ is maximum response rate constrained down spinning reserve related to thermal unit n**.**

The AC-OPF model in this paper is formulated as a mixed integer, nonlinear, non-convex, and non-smooth optimization problem with discontinuous solution space. The inclusion of non-convex constraints and discrete variables highly increases the complexity of this problem.

2.1. Wind Model

The uncertainty of wind speed affects the wind generation and also the AC-OPF problem. Fig. 1 presents a normal power curve for a WG.

Uncertainties related to wind speed are modeled and the output power of a wind generator can be represented using the equation between the generator output power and the wind speed using equation (17):

$$P(v_w) = \begin{cases} 0 & (v < v_{in} \; and \; v > v_o) \\ P_r \times \dfrac{(v - v_{in})}{(v_r - v_{in})} & (v_{in} \leq v \leq v_r) \\ P_r & (v_r \leq v \leq v_o) \end{cases} \quad (17)$$

Where $P(v_w)$ is the output power of WG; P_r is the rated wind power output; and v_{in}, v_r and v_o are the cut-in wind speed, nominal wind speed and cut-out wind speed, respectively. The model of wind turbines and other constraints (excluding spinning reserve constraints) are in [36].

Thus, the wind turbine output power is bringing together discrete and continuous random variables. For example, wind turbine output power works as a discrete random variable between v_r and v_o and a continuous random variable between v_{in} and v_r.

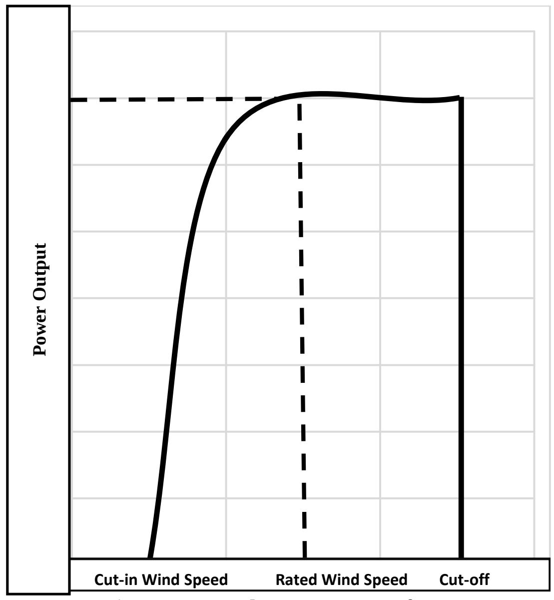

Fig. 1. Normal power curve for a WG.

3. PROPOSED APPROACH

Particle Swarm Optimization (PSO) was first presented by Dr. James Kenndy and Dr. Eberhart in 1995. They discovered this optimization approach by observing the behavior of flocks of birds. PSO algorithm is an adaptive technique based on social psychological symbol. A population of individuals (particles) is developed by cooperation and competition among the particles through iterations. Each particle represents a possible solution to a problem. By analyzing a simplified social system, this method has been introduced to solve non-linear optimization problems. Each individual keeps track of its coordinates in the n-dimensional search space, which are followed by the best particle (solution). The elementary basics of PSO are explained in [37].

3.1. Improved Particle Swarm Optimization Formulation

The overall approach of IPSO to have the AC-OPF problems solved includes the following steps:

1. Read data and parameters
2. Produce initial particles
3. Use a AC power flow model to find out the generation and total fuel cost considering operational constraints
4. Evaluate the validity of each solution
5. Generate the population of offspring
6. Check the boundary constraints
7. Check the ending conditions. If the ending conditions are provided, go to step 8, otherwise, go to step 3.
8. Report the results

In this algorithm, nPop particles are scattered randomly in the problem space and each particle has a position and a velocity.

To update the position of each particle, Equation (18) is used:

$$X_j^{k'} = X_j^k + V_j^{k+1} \tag{18}$$

Where, X is the position and V is the velocity. The velocity is as follows:

$$V_j^{k+1} = w.V_j^k + C_1 .rand\left(Pbest_j^k - X_j^k\right) + C_2 .rand\left(Gbest^k - X_j^k\right) \tag{19}$$

C_1 and C_2 are decision coefficients known as cognitive and social components, respectively, which are acceleration constants to vary the speed of each particle towards Pbest and *Gbest. Pbest* (personal best) is the best solution (fitness) the particle has achieved. *Gbest* (global best) is considered another best value that is considered the overall best value and its location is obtained by any particle in the population. C_1 and C_2 are normally considered 2 and w is the inertia weight which is [38]:

$$w = \mathrm{w_{max}} - (\mathrm{w_{max}} - \mathrm{w_{min}}) * (\mathrm{iter}/\mathrm{iter_{max}}) \tag{20}$$

Where: $w_{max} = 1.5, w_{min} = 0.5$

For velocity limits, Equations (21) and (22) are used as follows:

$$VelMax = VarMax - VarMin \tag{21}$$

$$VelMin = -VelMax \tag{22}$$

Where, $VelMin$ and $VelMax$ are the minimum and maximum velocity of the particles, respectively, that these limits give the algorithm more search space.

In this work, velocity mirror effect is used. It is when the particle is out of its area; the particle is mirrored and will be again in its area. So, as a result the quality of the answer is improved.

Velocity mirror effect is as follows:

$$\text{If} \quad VarMin > X_j^k \quad or \quad VarMax < X_j^k \quad V_j^k = -V_j^k \tag{23}$$

The velocity and position updating mechanisms of IPSO enhance the computation efficiency and enable PSO to jump out of the local optimum in non-convex problems.

Each particle or individual is considered a solution in IPSO and it consists of real output power, bus voltage, taps of transformers and reactive power that is inserted by shunt capacitors. The tap setting is assumed to be 0.01 that is a discrete step. The process of IPSO starts with the generation of initial population. It means that the random generation of real output power, bus voltage, taps of transformers and reactive power injection takes place. So as a result, initial solutions are generated and the constraints are met. Then a power flow analysis (AC power flow) is implemented to check the limits and constraints of system operation. After evaluating the fitness of each solution, the offspring population is generated. Evolutionary programming competition is applied to choose better solutions (individuals). After the competition, the winner is introduced as the offspring. The velocity and position are updated using equations (18) and (19). After checking the boundary limits and if any individual is out of its inequality constraint, the position of the individual is set to its maximum or minimum point. If the end condition is satisfied, the algorithm will stop. If not, iteration number is increased and the steps are repeated. Fig. 2 shows the proposed IPSO flowchart.

4. SIMULATION RESULTS

In this paper, the AC-OPF problem of power system considering wind energy is tested using a modified IEEE 30 bus system [39]. The system consists of 20 loads, 4 tap changers, 41 transmission lines, 6 generators and 2 shunt capacitors. Fig. 3 shows the single line diagram of the IEEE 30 bus system. The parameters $c_1.c_2$ and ω of the proposed IPSO approach were tuned based on [38].

4.1. Obtained Results for Case 1

In this section, it is assumed that the taps of transformers are set on their default value and the capacitances of shunt capacitors are considered constant. Obtained results from the proposed IPSO are presented in Table 1 for this case and the results are compared with the ones of traditional PSO. All constraints are satisfied in both algorithms. According to the Table 1, it is observed that the proposed IPSO method obtains both decreased fuel cost and transmission losses than traditional PSO.

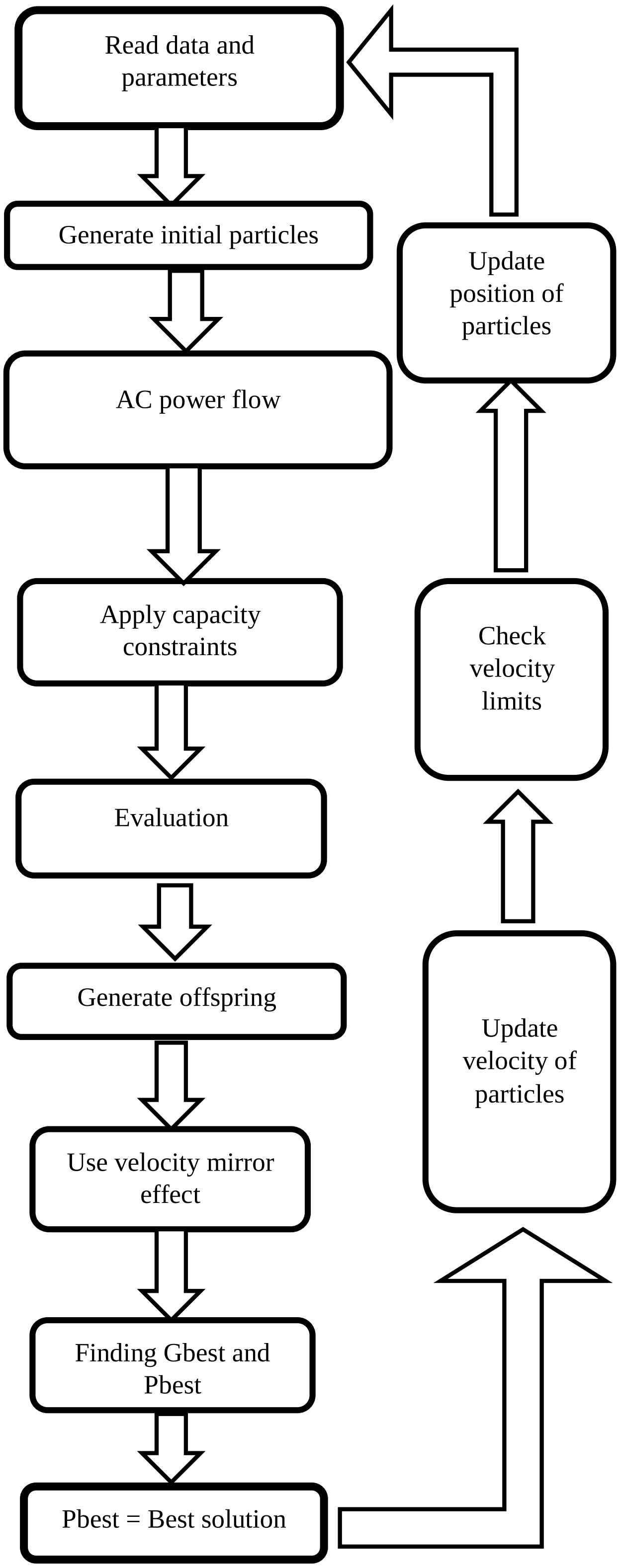

Fig. 2. Proposed IPSO flowchart.

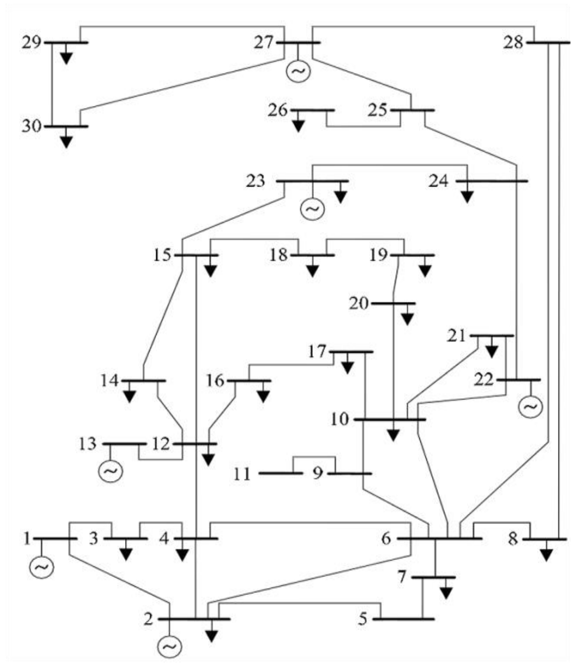

Fig. 3. Single line diagram of IEEE 30 bus system.

Table 1. Obtained results for case 1.

Parameters	Traditional PSO	Proposed IPSO
Pg1(MW)	42.56	42.44
Pg2(MW)	56.58	56.51
Pg3(MW)	22.61	22.56
Pg4(MW)	26.08	26.02
Pg5(MW)	15.97	16.07
Pg6(MW)	28.13	28.09
V1(pu)	1	1
V2(pu)	1.0123723	0.9984
V3(pu)	1.0817819	1.069
V4(pu)	1.0337916	1.0205
V5(pu)	1.0408789	1.0277
V6(pu)	1.0515513	1.0384
Total Generation(MW)	191.93	191.69
Fuel Cost($)	575.33016	574.60658
Transmission Losses(MW)	2.73	2.49

4.2. Obtained Results for Case 2 (Case1 + Transformer Tap Settings and Shunt Capacitors)

In this case, the taps of the transformers and capacity of the shunt capacitors are considered discrete variables and should be calculated by IPSO algorithm. The range of tap changers is between 0.9 and 1.05, with a step size of 0.01. The ranges of shunt capacitors are between 0 MVAR and 40 MVAR and step size of 1 MVAR. Obtained results from the proposed IPSO for this case are presented in Table 2 and compared with the results of traditional PSO. Again, it is seen that the proposed IPSO method obtains both lower fuel cost and lower transmission losses than traditional PSO. However, Tables 1 and 2 show that the transmission losses are reduced and consequently the fuel cost in case 2 is less than case 1.

To demonstrate the effectiveness and consistency of the proposed algorithm, 10 independent runs were performed for case 2 to determine IPSO's ability to reach an optimal or near-optimal solution. Table 3 presents the statistical data for case 2. The largest total fuel cost is 576.8522 \$/h, the best total fuel cost is 573.7282 \$/h, the average total fuel cost is 574.8966 \$/h, the standard deviation of total fuel cost is 0.682 \$/h. Results shown in Table 3, demonstrate the good performance of IPSO in solving the AC-OPF problem.

Table 2. Obtained results for case 2.

Parameters	Traditional PSO	Proposed IPSO
Pg1(MW)	42.51	42.43
Pg2(MW)	56.50	56.46
Pg3(MW)	22.58	22.47
Pg4(MW)	26.02	25.98
Pg5(MW)	16.01	15.96
Pg6(MW)	28.09	28.06
V1(pu)	1	1
V2(pu)	1.0124241	0.9984856
V3(pu)	1.0855253	1.0706053
V4(pu)	1.0359016	1.020478
V5(pu)	1.042503	1.0273115
V6(pu)	1.0535645	1.0386088
T1	1.02	1.05
T2	0.90	0.96
T3	1.03	1.03
T4	0.90	0.93
Qc,1(MVAR)	7	8
Qc,2(MVAR)	10	12
Total Generation(MW)	191.71	191.36
Fuel Cost(\$)	574.5243	573.7282
Transmission Losses(MW)	2.51	2.16

Table 3. Statistical data for case 2.

	Worst	Best	Mean	Standard deviation
Total generation (MW)	191.763	191.36	191.592	0.120
Total fuel cost (\$/h)	576.8522	573.7282	574.8966	0.682
Transmission loss (MW)	2.563	2.160	2.392	0.133

4.3. Obtained Results for Case 3 (Case2 +Wind Generator)

In this case, we study the influences of wind energy on fuel cost, transmission losses, up and down spinning reserves. Wind generators supply a part of the power system load and change the flow of transmission lines. So, power system transmission losses, operation costs and spinning reserves will change. Also, where the wind generators are located and different wind speed change the transmission losses. It is assumed that wind turbine generator is first on bus 3, a bus near the generators. Then, it is assumed that wind turbine generator is on bus 11, a bus located at the end of the transmission lines. Obtained results from the proposed IPSO for both locations of wind generator are presented in Table 4. This table shows different locations of wind generator, led to different transmission losses. In addition, the results show that to reduce transmission losses, the best place for the location of a wind generator is a bus located at the end of the transmission network. Also, Fig. 4 shows the convergence curve of the IPSO algorithm for wind turbine generator on bus 11.

However, this paper studies the influences of wind generation on up and down spinning reserves. Up and down Spinning reserves are calculated by equations (13) to (16). In this case, r%, the percentage of wind generation contributing to up and down spinning reserve is 50%, and *s%*, the percentage of load related to up spinning reserve is 10%. It is assumed that wind generator with capacities of 40% of the load of the power system is on bus 11. Table 5 shows the numerical results of down and up spinning reserves. The first column of Table 5 shows that wind speed varies from 5 m/s to 14 m/s. The results obtained for up spinning reserve necessity $(\sum_{i=1}^{I} Pl_i \times s\% + P_W \times r\%)$ and down spinning reserve necessity $(P_W \times r\%)$ are shown in columns 2 and 3, respectively. Also, the results obtained for up spinning reserve capacity $(\sum_{n=1}^{N_G} S_n^U)$ and down spinning reserve capacity $(\sum_{n=1}^{N_G} S_n^D)$ are shown in columns 4 and 5, respectively.

The results presented in table 5 show that the generation of the wind generator goes up as the speed of the wind increases. As a result, up spinning reserve necessity and down spinning reserve necessity increase. The generation of thermal generators and the down spinning reserve capacity decrease with respect to generation growth of the wind generator. However, the up spinning reserve capacity remains constant.

Table 4. Transmission losses with wind generation locations.

Connected bus		Transmission Losses (MW)	Total Fuel Cost ($)
Bus no.	Load (MW)		
3	2.4	2.08	560.014
11	0	1.83	558.939

Table 5. Spinning reserves calculation.

Wind Speed (m/s)	Up Spinning Reserve Necessity (KW)	Down Spinning Reserve Necessity (KW)	Up Spinning Reserve Capacity (KW)	Down Spinning Reserve Capacity (KW)
5	22629	3709	55000	45000
6	26339	7419	55000	43525
7	30049	11129	55000	40841
8	33759	14839	55000	37956
9	37469	18549	55000	35921
10	41178	22258	55000	34612
11	44888	25968	55000	28524
12	48598	29678	55000	24127
13	52308	33388	55000	20746
14	56018	37098	55000	15235

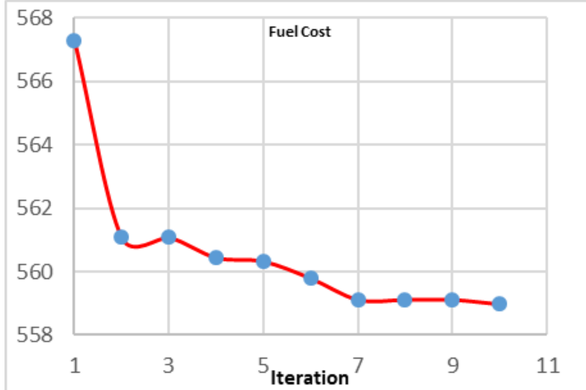

Fig. 4. Convergence curve of the IPSO algorithm.

In addition, Table 5 shows that when the wind speed becomes higher than 11 m/s, the down spinning reserve capacity cannot satisfy the down spinning reserve necessity. Also, when the wind speed becomes more than 13 m/s, the up spinning reserve capacity cannot satisfy the up spinning reserve necessity. In other words, when the wind speed becomes higher than 11 m/s, no solution is obtained for the AC-OPF problem. This problem creates a fundamental limit for AC-OPF problem considering wind energy.

In order to overcome the operational risk due to the wind energy, the wind generator installation capacity should decrease or additional spinning reserve capacities should be supplied.

5. CONCLUSION

This paper proposes an IPSO algorithm to solve AC optimal power flow problem considering wind generation system. Also, we study the effects of transformer tap settings and shunt capacitors on fuel cost and transmission losses. The results show that transmission losses are influenced by the location of wind generators and the best place for the wind generator is a bus located at the end of transmission network. Based on the results obtained in this paper, although with increasing wind energy production in the power system, transmission losses and fuel cost decrease, up and down spinning reserves requirements increase and operational risk due to wind energy also increase.

NOMENCLATURE

A. Indices and sets

l	Index of branches
n	Index of thermal units
i/j	Index of buses.
B	Number of branches
N_G	Number of thermal units
S_i^n	Set of thermal units connected to bus *i*
$\lvert V_i \rvert / \lvert V_j \rvert$	Voltage magnitudes of buses *i* and *j*
δ_i / δ_j	Voltage angles of buses *i* and *j*
FC	The fuel cost
$P(v_w)$	Power output of wind generator
Pl_i	Active load of bus *i*
Ql_i	Reactive load of bus *i*
B_{ij}	Susceptance of the branch *l* between buses
V^k	Voltage magnitude of bus k

S_i^w Set of wind generators connected to bus *i*

B. Parameters and Variables

$A_n.B_n.C_n$ The coefficients of the quadratic cost function

Q_{min}^C / Q_{max}^C Maximum/minimum limits of Q^C

BF^l Transmission limit of branch *l*

BF_{max}^l Maximum Transmission limit of BF^l

θ_{ik}^{phase} Setting of the phase shifter *i*-*k*;

$\theta_{ik}^{phase\ min} / \theta_{ik}^{phase\ max}$ Maximum/minimum limits of θ_{ik}^{phase}

$S_{U,max}^n$ Maximum response rate constrained up reserve related to thermal unit *n*

$S_{D,max}^n$ Maximum response rate constrained down spinning reserve related to thermal unit *n*

C_1 Cognitive component

C_2 Social component

G

G_{ij} Conductance of the branch *l*

P_n Generation of unit *n*

V_{min}^k / V_{max}^k Minimum/maximum limits of bus

Γ_{nk} Tap setting of the tap-changing transformer *n*-*k*

$\Gamma_{nk}^{min} / \Gamma_{nk}^{max}$ Maximum/minimum limits of Γ_{nk}

Q^C Reactive power injection of capacitors

S_n^U Up spinning reserve capacity of thermal unit *n*

S_n^U Up spinning reserve capacity of thermal unit *n*

S_n^D Down spinning reserve capacity of thermal unit *n*

s% Percentage of active loads for up spinning reserve

r% Percentage of wind generation related to up and down spinning reserve

$P(v_w)$ Output power of wind generator

P_r Rated wind power output

v_{in} Cut-in wind speed

v_r Nominal wind speed

v_o Cut-out wind speed

TL Transmission losses.

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