Wind Driven Optimization Approach based Multi-objective Optimal Power Flow and Emission Index Optimization

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Abstract: This paper proposes one of the optimization methods based on atmospheric motion. It is a global optimization nature-inspired method such as Wind Driven Optimization (WDO) approach to solve the Optimal Power Flow (OPF) and Emission Index (EI) in electric power systems. Our main aim is to minimize an objective function necessary for a best balance between the energy production and its consumption, which is presented as a nonlinear function, taking into account of the equality and inequality constraints. The WDO approach is nature-inspired, population based iterative heuristic optimization algorithm for multi-dimensional and multi-modal problems. WDO method have been examined and tested on the standard IEEE 30-bus system and IEEE 57-bus system with different objectives that reflect total active power generation cost, the active power losses and the emission index. The results of used method have been compared and validated with known references published recently. The results are promising and show the effectiveness and robustness of proposed approach.

Keywords: Optimization, Swarm intelligence, Optimal power flow, Emission index, Wind driven optimization.

Nomenclature: Optimization, Swarm intelligence, Optimal power flow, Emission index, Wind driven optimization.

| Symbols | Definition |
|---------|------------|
| ak, bk, ck | Cost coefficients w/o valve-point. |
| dk, ek | Cost coefficients w/ valve-point. |
| αk, βk, γk, ζk, ηk | Emission coefficients |
| f(x, u) | Objective function. |
| f1 | Cost function w/o valve-point. |
| f2 | Cost function with valve-point |
| f3 | Power losses function. |
| f4 | Emission index function |
| f5 | Cost and active loss function |
| f6 | Cost and emission function |
| f7 | Cost, power loss and emission |
| g(x, u) | Inequality constraints. |
| h(x, u) | Equality constraints. |
| nb | Total number of buses. |
| nB | Total number of branches. |
| ng | Total number of generators. |
| nL | Total number of branches. |
| nT | Total number of transformers |
| nCom | Total number of compensators |
| T | Tap settings transformers. |
| u | Control variables vector |
| x | Stat variables vector |
The emission index, or environmental index, is considered an important indicator from a conservation point of view [4]. Several strategies have been proposed and discussed to reduce atmospheric emissions.

The OPF problem has a long history of development of more than 58 years [1]. Since the OPF problem was first discussed by Carpenter in 1962, then formulated by Dommel and Tinney in 1968 [5].

The main purpose of solving the OPF problem is to calculate the optimal operating condition of the power system and corresponding settings for the economic operation of the control variables, by optimizing a specific objective taking into account economic and security constraints, such as equality and inequality constraints [1, 6, 7].

Over the past few years, many methods have been used to solve the OPF and EI problems like; Quadratic programming method (QP) [8], Newton and Qassi-Newton methods [9-11], Linear and non-linear programming methods, and nonlinear internal point methods (IPM) [12-16].

In the last two decades, and in order to solve the OPF and EI problems, several methods of optimization are formulated such as Artificial bee colony (ABC) and Incremental artificial bee colony [17-25], Bacterial foraging algorithms (BFA) and hybrid fuzzy based Bacterial foraging algorithm [26-27], Artificial neutral networks (ANN) [29, 30], Harmony search (HS) [31, 32], Cuckoo search algorithm (CSA) [33], Evolution programming (EP) [34, 35], Differential evaluation (DE) [36-39], Modified differential evaluation (MDE) [40-44], Tabu search (TS) [45-47], Simulated annealing (SA) [48-49], Gravitational search algorithms (GSA) [50-52], Evolutionary algorithm [53-55], Genetic algorithms (GA) [56-60], Particle swarm optimization (PSO) [61-69], Modified Particle swarm optimization (MPSO) [70-72], Distributed Sobol Particle swarm optimization (DSPSO) [73], Ant colony optimization (ACO) [74-79], Firefly Algorithm (FFA) [80-82], Tree-seed algorithm (TSA) [83], Sine-cosine algorithm (SCA) [84], Crow search algorithm (CSA) [85], Hybrid particle swarm optimization-differential evolution (FAHSPO) [86], Modified imperialist competitive algorithm (MICA) [87], Grey wolf optimizer (GWO) [3, 38, 88-96], Shuffled frog leaping algorithm (SFLA) and Modified SFLA [48, 97-98], Electromagnetism-like mechanism method (ELM) [99], Ant-lion optimizer [100], Interior search algorithm [101], and more recently the Wind driven optimization (WDO) method [102-112] were successfully utilized since their introduction to the literature as single objective optimization algorithm, Machine Learning and Modified grasshopper optimization Algorithms [113,114], Rao Algorithm [115], Hamiltonian Technique [116], Artificial Eco System optimization [117-118], Teaching-Learning-Studying-Based Optimization [119] and Combining Deep Learning [120], Artificial Fish Swarm Algorithm [121]. Variants of these algorithms were proposed to handle multi-objective functions in electric power systems.

The WDO is a natural-inspired algorithm based on heuristics techniques [105]. This promising algorithm is implemented firstly to solve the electromagnetic problems in communication engineering studies [106].

2. Problem Formulation

The OPF and EI are nonlinear optimization problems, represented by a predefined objective function \( f(x, u) \), subject to a set of equality and inequality constraints \([18, 64]\). Generally, these problems can be expressed as follows.

\[
\text{Min } f(x, u) \tag{1}
\]

Subject to

\[
h(x, u) = 0 \tag{2}
\]

\[
g(x, u) \leq 0 \tag{3}
\]

\[
x_{\text{min}} \leq x \leq x_{\text{max}} \text{ and } u_{\text{min}} \leq u \leq u_{\text{max}} \tag{4}
\]

Where \( f(x,u) \) is a scalar objective function to be optimised, \( h(x,u) \) and \( g(x,u) \) are, respectively, the set of nonlinear equality constraints represented by the load flow equations and inequality constraints consists of state variable limits and functional operating constraints. \( x \) and \( u \) are the state and control variables vectors respectively. \( x_{\text{min}}, x_{\text{max}}, u_{\text{min}} \) and \( u_{\text{max}} \) are the acceptable limits of variables. Hence, state variables vectors \( x \) can be expressed as given

\[
x' = \{p_{c1}, V_{r1}...V_{rn}, Q_{o1}...Q_{om}, S_{1}...S_{m}\} \tag{5}
\]

Where, \( p_{c}, Q_{o}, V_{r} \) and \( S_{k} \) are the generating active power at slack bus, reactive power generated by all generators, magnitude voltage of all load busses and apparent power flow in all branches, respectively. \( n_{r}, n_{L} \) and \( n_{t} \) are, respectively, the total number of generators, the total number of load busses and the total number of branches.

The set control parameters are represented in terms of the decision vector \( u \) as follows:

\[
u' = \{p_{c},...p_{m}, v_{r1}...v_{rn}, Q_{o},...Q_{om}, T_{1},...T_{m}\} \tag{6}
\]

Where, \( p_{c} \) are the active power generation excluding the slack generator, \( V_{r} \) are the generators magnitude voltage, \( T \) is tap settings transformers, and \( Q_{o} \) are the reactive power compensation by shunt compensator, \( n_{r} \) and \( n_{t} \) are the total number of transformers and the total number of compensators units, respectively.
2.1. Single-Objective Function

In general, the single-objective function is a nonlinear programming problem. In this paper, four single objectives commonly found in OPF and EI have been considered who are the generation cost without and with valve-point effect, \( f_1 \) and \( f_2 \), respectively, the active power losses \( f_3 \), and the emission index optimization \( f_4 \).

2.1.1. Cost Without Valve-Point Optimization

The objective function of cost optimization \( f_i \) of quadratic cost equation for all generators as given below

\[
f_i = \min \sum_{k=1}^{n_g} C(P_{sk}) = \min \sum_{k=1}^{n_g} a_k + b_k P_{sk} + c_k P_{sk}^2
\]

Where \( f_i \) is the total generation cost in ($/h)? \( P_{sk} \) and \( n_g \) are the active power output generated by the \( k \)th generator and the total number of generators. \( a_k \), \( b_k \) and \( c_k \) are the cost coefficients of the generator \( k \).

2.1.2. Cost with valve-point optimization

Generally, when every steam valves begins to open, the valve-point shows rippling. However, the characteristics of input-output of generation units make nonlinear and non-smooth of the fuel costs function. To consider the valve-point effect, the sinuosidal function is incorporated into the quadratic function \[18, 19\]. Typically, this function is represented as follows

\[
f_2 = \min \sum_{i=1}^{n_g} [d_i + b_i P_{sk} + c_i P_{sk}^2] + d_i \sin(e_i (P_{sk}^{max} - P_{sk}))
\]

Where \( d_i \) and \( e_i \) are the cost coefficients of unit with valve-point effect.

2.1.3. Active Power Loss Optimization

The active power loss function \( f_3 \) in (MW) to be minimized can be expressed as follows

\[
f_3 = \sum_{k=1}^{n_b} G_{kj} [V_k^2 + V_j^2 - 2V_k V_j \cos \theta_k]
\]

Where, \( V_k \) and \( V_j \) are the voltage magnitude at buses \( k \) and \( j \), respectively, \( G_{kj} \) is the conductance of line \( kj \), \( \theta_k \) is the voltage angle between buses \( k \) and \( j \) is the total number of buses.

2.1.4. Emission optimization

The emission function is the sum of exponential and quadratic functions of real power generating. Using a quadratic equation, emission of harmful gases is calculated in (ton/h) as given below

\[
f_4 = \min \sum_{k=1}^{n_g} 10^{-2} (\alpha_k + \beta_k P_{sk} + \gamma_k P_{sk}^2) + \zeta_k \exp(\lambda_k P_{sk})
\]

Where, \( f_4 \) is the emission function in (ton/h), \( \alpha_k, \beta_k, \gamma_k, \zeta_k \) and \( \lambda_k \) are the emission coefficients of the generator \( k \).

2.2. Bi-objective Function

2.2.1. Cost and active power loss optimization

When the optimization is the cost and the active power losses together, the bi-objective function as given below

\[
f_5 = f_2 + f_4 = \omega_1 f_1 + \omega_2 f_2, \text{ or } \omega_1 f_2 + \omega_2 f_4 \]

Where \( \omega_1 \) and \( \omega_2 \) are the weighting factors.

2.2.2. Cost and Emission Optimization

Emission is needs to minimize the generation cost and emission. The objective function is

\[
f_6 = \min\left(f_1 + Df_4 \right) = \min\left(f_2 + Df_4 \right)
\]

\( f_6 \) is the total cost-emission in ($/h), and \( D \) is the price penalty factor in ($/ton).

2.2. Multi-Objective Optimization

All objective functions discussed before are used to solve the multi-objective OPF and EI problems. Therefore, the multi-objective problems can be stated as follows

\[
f_7 = \omega_1 f_1 + \omega_2 f_2 + \omega_3 f_4 \text{ or } \omega_1 f_2 + \omega_2 f_3 + \omega_3 f_4
\]

The function used in the case of weighted aggregation is given by equation (12).

\[
Min F = \sum_{i=1}^{n_i} \omega_i f_i \text{ with } \omega_i \geq 0 \text{ and } \sum_{i=1}^{n_i} \omega_i = 1
\]

Where, \( \sum_{i=1}^{n_i} \omega_i = 1 \) & \( i = 1:n_f \), \( \omega_i \) is the weighting factor and \( n_f \) is the number of objective function.

2.3. Equality Constraints

These equality constraints are the sets of nonlinear load flow equations that govern the power system, i.e.:
\[
\begin{align*}
\begin{cases}
P_{sk} = P_i + P_{sk} \\
Q_{sk} - Q_{comk} = Q_k + Q_{sk}
\end{cases}
\end{align*}
\] (15)

Where \(P_{sk}\) and \(Q_{sk}\) are, respectively, the scheduled active and reactive power generations at bus \(k\). \(P_i\), \(Q_i\) are the active and reactive power injections at bus \(i\). \(P_{sk}\), \(Q_{sk}\) and \(Q_{comk}\) are the active and reactive power loads at bus \(k\) and the reactive power compensation at bus \(k\).

2.4 Inequality Constraints

The inequality constraints \(g(x,u)\) are represented by the system operational and security limits, listed below:

- **Active and reactive power generations limits**:
  \[
  P_{sk}^{\text{min}} \leq P_{sk} \leq P_{sk}^{\text{max}} \quad \text{where} \quad k = 1,\ldots,n_k
  \] (16)
  \[
  Q_{sk}^{\text{min}} \leq Q_{sk} \leq Q_{sk}^{\text{max}} \quad \text{where} \quad k = 1,\ldots,n_k
  \] (17)

- **Voltage magnitudes and angles limits**:
  \[
  V_k^{\text{min}} \leq V_k \leq V_k^{\text{max}} \quad \text{where} \quad k = 1,\ldots,n_b
  \] (18)
  \[
  \theta_k^{\text{min}} \leq \theta_k \leq \theta_k^{\text{min}} \quad \text{where} \quad k = 1,\ldots,n_b
  \] (19)

- **Tap settings transformers limits**:
  \[
  T_k^{\text{min}} \leq T_k \leq T_k^{\text{max}} \quad \text{where} \quad k = 1,\ldots,n_T
  \] (20)

- ** Reactive power compensation limits**:
  \[
  Q_{comk}^{\text{min}} \leq Q_{comk} \leq Q_{comk}^{\text{max}} \quad \text{where} \quad k = 1,\ldots,n_{com}
  \] (21)

Where, \(n_i\), \(n_f\), \(n_{com}\), \(T\) and \(Q_{com}\) are total number of buses, the total number of transformers, the total number of compensators, the transformers tap settings and the reactive power compensation, respectively.

- **Security constraint limits**:
  \[
  S_{ij} \leq S_{ij}^{\text{max}} \quad \text{where} \quad k = j = 1,\ldots,n_{\text{bus}}
  \] (22)

\(S_{ij}^{\text{max}}\) is the maximum apparent power flow.

2. Wind Driven Optimization Technique

The WDO algorithm was first introduced in 2010 [108]. The WDO is one of the optimization methods based on atmospheric motion, and it is global optimization nature-inspired method. This technique works on population based global heuristic algorithms for multi-dimensional and multi-dimensional models in the research field to apply constraints [104, 107].

3.1. Context Theory and Destination Of WDO

In the atmosphere, wind blows in an effort to make equal air pressure [106]. More exclusively, the air is used to move from high pressure to low pressure at a velocity, which is proportional to the pressure gradient [104]. Furthermore, some assumptions and simplifications are formulated in derivation of the WDO algorithm. The starting point in the development of WDO is with Newton’s second law of motion, which is known to provide very accurate results when applied to the analysis of atmospheric motion [106].

\[
\vec{\rho} \vec{\omega} = \sum \vec{F}_i
\] (23)

Where, \(\vec{\omega}\) is the acceleration vector, \(\rho\) is the air density for an infinitesimal air parcel, and \(\vec{F}_i\) are the all forces acting on the air parcel [108]. The equation that relates air pressure to its density and temperature is given by the ideal gas law, formulated as follows

\[
P = \rho RT
\] (24)

In Eq. (24), \(P\), \(R\) and \(T\) are, respectively, the pressure, the universal gas constant, and the temperature. In Eq. (23), there are four main forces that either cause the wind to move in a specific direction or deflect it from its path [102]. The most observable force causing the air to move is the pressure gradient force \(\vec{F}_{\text{PG}}\), although the friction force \(\vec{F}_F\), the gravitational force \(\vec{F}_g\) and the Coriolis force \(\vec{F}_c\) [104, 108]. Knowing that the force of the degree of pressure acting a very important role in air movement.

By assuming air has a finite volume \((\delta V)\), the physical force equation because of pressure gradient can be expressed as [102].

\[
\vec{F}_{\text{PG}} = -V \delta P \vec{V}
\] (25)

The frictional force oppose the air parcel motion started by \(F_{\text{PG}}\), and can be expressed as

\[
\vec{F}_F = -\rho \alpha \vec{v}
\] (26)

The gravitational force pull the air parcel to the center of the earth expressed as

\[
\vec{F}_G = \rho \vec{V} \delta V \vec{g}
\] (27)

The Coriolis is caused by the rotation of earth, and deflects the path of wind from one dimension to another. This force will work in such a way that velocity in one direction is influenced by velocity of another direction [108]. It can be expressed as

\[
\vec{F}_C = -2\Omega \vec{v}
\] (28)
Where, \( \nabla P \) is the pressure gradient, \( \nabla v \) represents an infinitesimal air volume, \( \alpha \) is the frictional coefficient, \( \mathbf{v} \) is the wind velocity vector, \( \mathbf{g} \) is the gravitational acceleration, and \( \Omega \) represent the rotation of earth.

Taking for simplicity, the acceleration equal to \((\Delta u/\Delta t)\), the time step \(\Delta t=1\) and \(\nabla v = 1\). Therefore, the summation of including \(\mathbf{F}_{pg}, \mathbf{F}_{p}, \mathbf{F}_{g}, \mathbf{F}_{C}\) in the total force described in Eq. (25) can be rewritten as

\[
\rho \Delta v = \rho \mathbf{v} \Delta t = \mathbf{F}_{pg} + \mathbf{F}_{p} + \mathbf{F}_{g} + \mathbf{F}_{C} = \rho \mathbf{g} + (-\nabla P) + (-\rho \alpha \mathbf{v}) + (-2\Omega \mathbf{v}) \quad \text{v} \quad \text{t}
\]

(29)

The change in velocity in Eq. (29) can be extracted from modifying the Eq. (30) based on Eq. (24) and division by \((RT/P)\) [109].

\[
\Delta v = v_{(k+1)} - v_{(k)} = g + (-\nabla P) + (-\rho \alpha \mathbf{v}) + (-2\Omega \mathbf{v}) \quad \text{v} \quad \text{t}
\]

(30)

The vector \( g \) can be written as \( g = |g|(0 - x(k)) \) [103, 109]. The pressure gradient is the force that attempts to move an air parcel from its current position into optimal pressure. It can be expressed as

\[-\nabla P = P_{(opt)} - P_{(k)}(x_{(opt)} - x_{(k)}) \]

All coefficients in the last term of Eq. (30) are collected to be a single term as \(c = -2\Omega RT\) [111]. Eq. (30) can be modified as in Eq. (31).

\[
\Delta v_{(k+1)} = \left[ (1 - \alpha) v_{(k)} \right] + \left[ \mathbf{g}(x_{(k)}) \right] + \frac{RT}{P_{(k)}} \left[ P_{(opt)} - P_{(k)}(x_{(opt)} - x_{(k)}) \right] + \frac{c v_{(k)}}{P_{(k)}} \quad \text{v} \quad \text{t}
\]

(31)

On the basis of ideal gas law equation from Eq. (24), and for simplicity, assuming that a single time step \((\Delta t=1)\), the air density, \( \rho \) can be written as the pressure [104]. Based on Newton’s second law of motion, the velocity vector \( \mathbf{v} \) is

\[
\mathbf{v}_{(k+1)} = \left[ (1 - \alpha) \mathbf{v}_{(k)} \right] + \mathbf{g}(x_{(k)}) + \left[ \frac{P_{(opt)}}{P_{(k)}} \right] \left[ RT(x_{(opt)} - x_{(k)}) \right] + \frac{c v_{(k)}}{P_{(k)}} \quad \text{v} \quad \text{t}
\]

(32)

The updated velocity of the next iteration \( v_{(k+1)} \) shown in Eq. (32) depends on the velocity of current iteration \( v_{(k)} \), the air parcel of current position in search space \( x_{(k)} \), the distance from the highest pressure point that has been found \( x_{(opt)} \), the maximum pressure \( P_{(opt)} \), the pressure at the current location \( P_{(k)} \), the temperature \( T \), the gravitational acceleration \( g \), the universal gas constant \( R \), the frictional coefficient \( \alpha \), and the Coriolis constant, \( \mathbf{c} \) [102-107]. Air parcel position is updated, after the velocity of parcel given by Eq. (32) is updated. This can be expressed as

\[
\mathbf{x}_{(k+1)} = \mathbf{x}_{(k)} + \mathbf{v}_{(k+1)} \Delta t
\]

(33)

In Eq. (33), \( \mathbf{x}_{(k+1)} \) represent that the air parcel vector would continue to move in its previous path with some opposition that is created due to friction. \( \mathbf{v}_{(k+1)} \) is an attractive force that pulls against the center of coordinate system. The time step \( \Delta t \) assuming that is the global best position. \( \mathbf{x}_{(k+1)} \) is a vector represent the deflecting force [107 - 109]. The WDO permits the air parcels to move only in the interval [-1, 1] for each dimension [110]. To check that the velocity amplitude is within the maximum and minimum limits in any dimension, the following equation is used [108].

\[
v' = \begin{cases} v_{\text{max}} & \text{if } v_{(k+1)} > v_{\text{max}} \\ v_{\text{min}} & \text{if } v_{(k+1)} < -v_{\text{max}} \end{cases}
\]

(34)

### 3.2. Implementation of WDO In OPF Problem

In order to implement the WDO method to solve the OPF and EI problems, the decision variables must be specified. The first step to execute the WDO method is the initialization, i.e. (the algorithm starts by randomly initializing the position and the velocity vectors). In the second step, after the execution of the optimization practice based on the WDO algorithm, the populations of air parcels are distributed randomly over the search space and at random velocities. In the third step, the values of the position and the velocity of each air parcel chosen in the previous step must be evaluated (objective function). The velocity would be updated and check the limits using Eq’s. (32) and (34), respectively. In the fifth step, the position of each air parcel must be updated and outgoing air parcels are verified to avoid violating limits. The updating iterations are tested according Eq. (33). Then, the above procedure would be repeated until reaching the maximum iterations.

### 4. Simulation & Results

The proposed WDO-based algorithm for solving OPF and EI problems has been applied to the IEEE 30-bus and IEEE 57-bus test systems. The numerical and graphical results are represented in these sections.

#### 4.1. IEEE 30-bus test system

The five generators system, IEEE 30-bus system is used throughout this work to test the proposed...
This system consists of 30 buses, 6 generators, units, and 41 branches, 37 of them are the transmissions lines, and 4 are tap changing transformers. One of these buses is chosen as a reference bus (slack bus), the buses containing generators are taken the PV buses, the remaining buses are the PQ buses or loads buses. It is assumed that 9 capacitors compensation is available at buses 10, 12, 15, 17, 20, 21, 23, 24, and 29. The network data, the cost and emission coefficients of the five generators are referred in [122]. The one-line diagram of IEEE 30-bus system is shown in Figure 1.

The total loads of active and reactive powers are 283.4 (MW) and 126.2 (MVAr), respectively, with 24 control variables. The basis apparent power used in this paper is 100 (MVA). The simulation results of load flow problem of test system are summarized in Table 1.

4.1.1. Case 1: Cost optimization

The objective functions of cost $f_1$ given in Eq. (7) is optimized. Therefore, in this case, the cost has resulted in 801.1347 ($/h), which is considered 8.3608 % lower than the initial case (load flow). Figure 2 shows the convergence characteristic of cost using WDO algorithm. Table 1 summarizes the optimal control variables of this case.

4.1.2. Case 2: Cost with valve-point effect optimization

The cost function $f_2$ given in Eq. (8) is optimized. Therefore, in this case, the cost has resulted in 826.37 ($/h), which is considered 5.4742 % lower than the initial case. The convergence characteristic of cost optimization for this case is introduced in Figure 2. Table 1 summarizes the optimal control variables of this case.

4.1.3. Case 3: Active Power Loss Optimization

The optimal control variables of this case are introduced in Table 1.

![Figure 1. One-line diagram of IEEE 30-bus system.](image1)

![Figure 2. Convergence of algorithm for cases 1 and 2.](image2)
Table 1. Single objective results of IEEE 30-bus system.

| Control variables | Basic Load flow | Optimal values | After optimization |
|-------------------|-----------------|-----------------|---------------------|
|                   |                 | Cost w/o valve  | Cost w/ valve       | Loss w/ valve      | Loss w/o valve | Emission |
|                   |                 | Case 1          | Case 2              | Case 3             | Case 4         |
| $P_{G2}$ (MW)     | 40.0000         | 48.2030         | 29.4689             | 79.5519            | 79.6882        | 77.5750  |
| $P_{G5}$ (MW)     | 0.0000          | 21.8059         | 16.0676             | 49.7269            | 49.7604        | 50.0000  |
| $P_{G8}$ (MW)     | 0.0000          | 19.3977         | 10.0938             | 34.8591            | 35.0000        | 27.3119  |
| $P_{G11}$ (MW)    | 0.0000          | 13.4665         | 10.1456             | 29.7040            | 29.6496        | 30.0000  |
| $P_{G13}$ (MW)    | 0.0000          | 12.0000         | 12.0379             | 39.6966            | 40.0000        | 40.0000  |
| $V_1$ (pu)        | 1.0600          | 1.0893          | 1.0671              | 1.0612             | 1.0565         | 1.0272   |
| $V_2$ (pu)        | 1.0450          | 1.0672          | 1.0472              | 1.0331             | 1.0392         | 0.9584   |
| $V_5$ (pu)        | 1.0500          | 1.0295          | 1.0006              | 1.0311             | 1.0407         | 0.9567   |
| $V_8$ (pu)        | 1.0700          | 1.0359          | 1.0180              | 1.0426             | 1.0407         | 0.9567   |
| $V_{11}$ (pu)     | 1.0900          | 1.0568          | 1.1000              | 1.0509             | 1.0940         | 1.0239   |
| $V_{13}$ (pu)     | 1.0900          | 1.0333          | 1.0707              | 1.0501             | 1.0334         | 1.0671   |
| $Q_{com10}$ (MVar)| 0.0000          | 4.0308          | 3.3442              | 4.3007             | 0.1324         | 1.4882   |
| $Q_{com12}$ (MVar)| 0.0000          | 2.4727          | 4.2582              | 3.5066             | 2.5973         | 1.3674   |
| $Q_{com15}$ (MVar)| 0.0000          | 2.8602          | 4.1133              | 3.1962             | 2.1219         | 5.0000   |
| $Q_{com17}$ (MVar)| 0.0000          | 2.5035          | 4.4476              | 2.3281             | 0.3839         | 0.0559   |
| $Q_{com20}$ (MVar)| 0.0000          | 3.4482          | 0.0652              | 4.6020             | 1.4640         | 1.8672   |
| $Q_{com21}$ (MVar)| 0.0000          | 0.8353          | 2.0983              | 3.5938             | 2.7041         | 1.3149   |
| $Q_{com23}$ (MVar)| 0.0000          | 3.1147          | 3.7974              | 4.9475             | 1.0174         | 0.0000   |
| $Q_{com24}$ (MVar)| 0.0000          | 1.3913          | 3.3311              | 2.2424             | 3.5296         | 4.7243   |
| $Q_{com29}$ (MVar)| 0.0000          | 2.2401          | 3.9877              | 4.3683             | 3.1557         | 3.4815   |
| $T_{6-9}$         | 0.9780          | 1.0019          | 1.0081              | 1.0061             | 1.0370         | 0.9018   |
| $T_{6-10}$        | 0.9690          | 1.0208          | 0.9984              | 1.0156             | 0.9963         | 1.0979   |
| $T_{8-12}$        | 0.9666          | 0.9800          | 0.9919              | 1.0125             | 1.0084         | 1.0039   |
| $T_{28-27}$       | 0.9320          | 0.9840          | 0.9597              | 1.0044             | 0.9817         | 0.9137   |
| Cost in ($/h)     | 874.2272        | **801.1347**    | **826.3700**        | **964.0800**       | **1025.9600**  | **954.3807** |
| Active power loss in (MW) | 17.5600 | 9.1924 | 12.1410 | **3.2327** | **3.2771** | 5.1640 |
| Emission (ton/h)   | 4.1000          | 0.3117          | 0.3211              | 0.2161             | 0.2162         | **0.2150** |
| Slack generator in (MW) | 260.9600 | 177.7193 | 217.7273 | 53.0943 | 52.5789 | 63.6770 |
| Average CPU time (s) | 19.8200 | 105.3330 | 90.3453 | 88.4539 | 82.1792 | 108.4624 |
Figure 3 shows the trend for convergence characteristics of active power losses using WDO algorithm. The active power loss minimization has dramatically decreased to 3.2327 (MW) and 3.2771 (MW) without and with valve-point effect, respectively, which is considered 81.5905 % and 81.3376 % lower than the basic case, that is, the case without optimization.

4.1.4. Case 4: Emission optimization

In this case, the emission reduction yielded 0.1763 (ton/h), which is considered 97.7962 % lower than initial case. The optimal settings of control variables for individual objective functions are detailed in Table 1. The convergence characteristics of emission using WDO method is shown in Figure 4.

4.1.5. Case 5: Cost and active loss optimization

The control variables of this case are tabulated in detail in Table 2. The cost in this case has resulted in 828.44 ($/h) and 861.32 ($/h) w/o and with valve-point, respectively. The active power loss w/o and with valve-point effect are, respectively, 5.7412 (MW) and 6.3312 (MW).

4.1.6. Case 6: Cost and emission optimization

The bi-objective optimization considering the cost and the emission are tabulated in Table 2. The control variables of this case are tabulated in detail in Table 2. The cost has resulted in 801.41 ($/h) and 826.29 ($/h) w/o and with valve-point effect, respectively. Figure 5 shows the convergence characteristics obtained in cases 5 and 6.

4.1.7. Case 7: Cost, Active Power Loss and Emission

The IEEE 30-bus control variables of multi-objective considering cost, active power loss and emission are presented in detail in Table 2.
### Table 2. Bi-objective results of IEEE 30-bus system

| Control variables | Optimal values |  |  |  |  |  |
|--------------------|----------------|---|---|---|---|---|
|                    | Case 5 | Case 6 | Case 7 | w/o valve | with valve | w/o valve | with valve | w/o valve-point | valve-point |
| $P_{G2}$ (MW)     | 54.8769 | 48.6969 | 49.8438 | 28.2085 | 51.2691 | 52.6613 |
| $P_{G5}$ (MW)     | 30.2127 | 27.5559 | 21.8352 | 15.9615 | 29.3629 | 28.9637 |
| $P_{G8}$ (MW)     | 34.0291 | 34.7321 | 21.3200 | 10.0390 | 34.8815 | 28.3500 |
| $P_{G11}$ (MW)    | 26.0009 | 22.2444 | 13.1581 | 10.0000 | 22.1273 | 22.6876 |
| $P_{G13}$ (MW)    | 21.4080 | 21.3438 | 12.0000 | 12.0000 | 22.3051 | 22.3247 |
| $V_{1}$ (pu)      | 1.0708 | 1.0766 | 1.0781 | 1.0890 | 1.0737 | 1.0794 |
| $V_{2}$ (pu)      | 1.0588 | 1.0612 | 1.0627 | 1.0576 | 1.0589 | 1.0648 |
| $V_{5}$ (pu)      | 1.0286 | 1.0339 | 1.0302 | 1.0266 | 1.0298 | 1.0363 |
| $V_{6}$ (pu)      | 1.0421 | 1.0463 | 1.0394 | 1.0318 | 1.0412 | 1.0400 |
| $V_{11}$ (pu)     | 1.0695 | 1.0425 | 1.0217 | 1.0110 | 1.0526 | 1.0176 |
| $V_{13}$ (pu)     | 1.0465 | 1.0557 | 1.0261 | 0.9998 | 1.0419 | 1.0351 |
| $Q_{com10}$ (MVAr) | 1.9299 | 2.2378 | 2.3725 | 4.4450 | 4.6826 | 3.2852 |
| $Q_{com12}$ (MVAr) | 3.5779 | 2.7680 | 2.8893 | 4.3708 | 3.3781 | 1.3729 |
| $Q_{com15}$ (MVAr) | 4.2918 | 2.1745 | 1.8944 | 1.9876 | 3.9585 | 3.8477 |
| $Q_{com17}$ (MVAr) | 2.1102 | 2.3225 | 3.1717 | 4.6924 | 1.1924 | 2.4007 |
| $Q_{com20}$ (MVAr) | 2.2800 | 3.6888 | 2.3260 | 4.3612 | 3.0944 | 1.9439 |
| $Q_{com21}$ (MVAr) | 2.0265 | 2.3431 | 1.9763 | 4.3877 | 2.3942 | 3.6115 |
| $Q_{com23}$ (MVAr) | 2.6643 | 1.5274 | 1.6074 | 2.1420 | 4.6949 | 2.3554 |
| $Q_{com24}$ (MVAr) | 2.2253 | 2.0667 | 3.6352 | 4.3589 | 2.3718 | 2.0941 |
| $Q_{com29}$ (MVAr) | 3.9133 | 2.3475 | 1.5725 | 0.1540 | 1.1799 | 3.3638 |
| $T_{6-9}$          | 0.9809 | 0.9753 | 1.0293 | 1.0801 | 0.9914 | 0.9890 |
| $T_{6-10}$         | 1.0281 | 0.9985 | 0.9314 | 1.0017 | 1.0167 | 0.9832 |
| $T_{T_{27-28}}$    | 1.0128 | 0.9823 | 1.0146 | 0.9950 | 1.0157 | 0.9978 |
| Cost in ($/h)     | 828.4400 | 861.3200 | 801.4100 | 826.2900 | 822.5800 | 863.0300 |
| Active power loss in (MW) | 5.7412 | 6.3312 | 8.9817 | 11.9343 | 6.0390 | 6.4499 |
| Emission in (ton/h) | 0.2524 | 0.2557 | 0.3106 | 0.4700 | 0.2499 | 0.1783 |
| Slack generator in (MW) | 122.6137 | 135.1582 | 174.2246 | 219.4134 | 129.4931 | 134.8625 |
| Average CPU time (s) | 112.5017 | 121.6664 | 99.8236 | 95.8352 | 79.0636 | 73.8949 |
Figure 5. Convergence of algorithm for cases 5 and 6.

Figure 6. Convergence of algorithm for case 7.

Figure 7. Convergence algorithm for case 7 with different population size.
When the valve-point is not in consideration, de
generation cost is the $822.58/h and $863.03/h with
valve-point effect is in consideration. The active power
losses and emission w/o and with valve-point effect for
this case are, respectively, 6.039 MW, 6.4499 MW,
0.2499 ton/h and 0.1783 ton/h.

Figure 6 shows the convergence characteristics
of multi-objective optimization obtained in case 7 without
and with valve-point effect with respect the number of
generation under cost optimization, losses optimization
and emission optimizations using proposed method.

For the IEEE-30 bus system, 24 control
variables (5 generators outputs excluding slack bus, 6
generators magnitude voltages, 4 transformers
tap and 9 reactive powers compensators) were optimized. Under
the same conditions i.e. control variables limits,
constraints and system data, the optimal solutions of
IEEE 30-bus test system using the WDO algorithm
reported in this paper are compared to some other
techniques reported in the literature.

The parameters of WDO method used in this
paper are the friction coefficient, $\alpha=0.4$, the gravitational
constant $g=0.2$, the wind velocity vector, $v=3$, the
coefficient $RT=3$ and the Coriolis constant, $c=0.4$.

The developed WDO has been implemented
and used to solve the OPF and EI problems of IEEE 30-
bus system under varying operating conditions. Figure 7
shows the convergence characteristics of WDO method
for case 6 with various population sizes applied to IEEE
30-bus system.

It is clearly shown that the WDO could effectively
find the optimum solution before the maximum iteration
was reached.

The proposed method to solve the OPF and the
EI problems is considered to have given the best results
because the results obtained using the WDO method are
better compared to those published recently in several
researches papers.

From Figures 5 and 6, all cases study of bi-
objective and multi-objective results obtained the
minimum values after 120 iterations.

4.2. IEEE 57-bus test system

In this case, the IEEE 57-bus system is
considered to investigate the effectiveness of the
proposed algorithm. The IEEE 57-bus system consists
of 7 generators at buses 1, 2, 3, 6, 8, 9, and 12, 17
transformers are located at branches 19, 20, 31, 37, 41,
46, 54, 58, 59, 65, 66, 71, 73, 76, and 80, 3 shunts are
considered at buses 18, 25 and 53, and 80 transmission
lines. The single-line diagram of this system and the
detailed data are given in [89].

4.2.1. Case 1: Cost optimization

The optimal settings of control variables for
individual objective functions are detailed in Table 3. The
convergence characteristic of this case is shown in
Figure 8.

4.2.2. Case 2: Cost and power losses optimization

The optimal settings of control variables for bi-
objective functions are detailed in Table 3. The
convergence characteristic of this case is shown in
Figure 8.

4.2.3. Case 3: Cost and emission optimization

The optimal settings of control variables for bi-
objective functions are detailed in Table 3. The
convergence characteristic of this case is shown in
Figure 8.

Figure 8. Convergence algorithm for cases 1, 2, 3 and 4 of IEEE 57-bus system.
### Table 3. Results of cases 1, 2, 3, and 4 of IEEE 57-bus system

| Control variables | Case 1 | Case 2 | Case 3 | Case 4 |
|-------------------|--------|--------|--------|--------|
| $P_{G2}$ (MW)     | 54.6750| 71.4940| 91.6446| 43.0780|
| $P_{G3}$ (MW)     | 73.2220| 74.9188| 43.1966| 81.3522|
| $P_{G6}$ (MW)     | 59.9617| 15.2784| 55.7033| 42.9193|
| $P_{G8}$ (MW)     | 482.8535| 501.7457| 503.7254| 474.0350|
| $P_{G9}$ (MW)     | 98.0371| 35.0817| 31.7962| 58.8914|
| $P_{G12}$ (MW)    | 336.7256| 383.2472| 388.1839| 389.1949|
| $V_1$ (pu)        | 1.0339 | 1.0094 | 1.0549 | 1.0024 |
| $V_2$ (pu)        | 1.0238 | 0.9962 | 1.0489 | 0.9914 |
| $V_3$ (pu)        | 1.0283 | 1.0129 | 1.0356 | 1.0145 |
| $V_6$ (pu)        | 1.0389 | 1.0318 | 1.0408 | 1.0295 |
| $V_8$ (pu)        | 1.0365 | 1.0506 | 1.0439 | 1.0432 |
| $V_{12}$ (pu)     | 1.0361 | 1.0519 | 1.0104 | 1.0546 |
| $Q_{com18}$ (MVAr)| 6.2847 | 10.9428| 28.5455| 14.7010|
| $Q_{com25}$ (MVAr)| 19.4961| 15.0816| 20.3682| 14.9048|
| $Q_{com53}$ (MVAr)| 18.8091| 15.3732| 20.1136| 9.9356 |
| $T_{21}$ (pu)     | 1.0181 | 0.9721 | 0.9765 | 0.9860 |
| $T_{24}$ (pu)     | 0.9366 | 0.9880 | 1.0544 | 1.0089 |
| $T_{26}$ (pu)     | 1.0331 | 1.0687 | 1.0546 | 0.9787 |
| $T_{29}$ (pu)     | 0.9999 | 0.9863 | 1.0062 | 0.9994 |
| $T_{32}$ (pu)     | 0.9779 | 0.9732 | 0.9981 | 1.0603 |
| $T_{34}$ (pu)     | 1.0351 | 0.9692 | 0.9963 | 0.9922 |
| $T_{36}$ (pu)     | 1.0354 | 1.0058 | 1.0342 | 1.0079 |
| $T_{41}$ (pu)     | 0.9365 | 0.9975 | 0.9864 | 1.0170 |
| $T_{45}$ (pu)     | 0.9537 | 0.9190 | 0.9796 | 0.9402 |
| $T_{46}$ (pu)     | 0.9994 | 1.0349 | 0.9960 | 1.0269 |
| $T_{51}$ (pu)     | 1.0011 | 0.9867 | 0.9953 | 0.9702 |
| $T_{52}$ (pu)     | 0.9735 | 1.0581 | 0.9925 | 1.0203 |
| $T_{53}$ (pu)     | 1.0853 | 0.9658 | 0.9584 | 0.9746 |
| $T_{56}$ (pu)     | 0.9419 | 1.0243 | 1.0366 | 0.9895 |
| $T_{57}$ (pu)     | 0.9664 | 0.9654 | 0.9619 | 1.0027 |
| $T_{58}$ (pu)     | 1.0132 | 1.0426 | 0.9637 | 1.0173 |
| Cost in ($/h)     | 42075.10| 42436.76| 41883.07| 42388.09|
| Power losses in (MW)| 23.89496| 23.0491| 27.1184| 20.6044|
| Emission in (ton/h)| 2.2788 | 3.2567 | 1.9167 | 2.4624 |
| Slack generation (MW)| 164.1014| 189.2383| 154.0954| 179.5996|
| CPU time (min)    | 23.6500| 20.2135| 21.2408| 18.0218|
| Methods  | Ref. | Cost ($/h) | Losses (MW) | Emission ($/ton) |
|----------|------|------------|-------------|------------------|
| Proposed | -    | 954.3807   | 5.1640      | 0.2150           |
| GA       | [3]  | 936.6200   | 9.7000      | 0.2117           |
| HGA      | [28] | 984.9400   | 10.4300     | -                |
| MSA      | [53] | 944.5003   | 3.2858      | 0.2048           |
| MPSO     | [53] | 879.9464   | 7.0467      | 0.2324           |
| PSGWO    | [96] | 944.5120   | 3.2358      | 0.2048           |
| DE       | [23] | 963.0010   | -           | -                |
| MDE      | [53] | 927.8066   | 4.8539      | 0.2092           |
| MFO      | [53] | 945.4553   | 3.4295      | 0.2048           |
| FPA      | [53] | 948.9490   | 4.4920      | 0.2052           |
| ABC      | [17] | 944.4391   | 3.2470      | 0.2048           |
| IABC     | [24] | -          | -           | 0.1943           |
| MOGWO    | [3]  | 945.3785   | 3.5519      | 0.2049           |
| CSA      | [85] | 950.9308   | 3.5708      | 0.2010           |
| HPSO-DE  | [86] | -          | -           | 0.2048           |

Table 4. Comparison of obtained results for the case 4 of IEEE 30-bus system.
4.2.4. Case 4: Cost, losses and emission optimization

The optimal settings of control variables for multi-objective functions are detailed in Table 3. The convergence characteristic of this case is shown in Figure 8.

Tables 4 and 5 shows a comparison between the obtained single and multi-objective results of costs, power losses and emission with the results obtained in literature.

5. Conclusion

The WDO approach is successfully implemented in this paper to find the optimum control variables of OPF and EI problems for several cases studies using two power systems which are IEEE 30-bus and IEEE 57-bus test systems.

The versatility of the OPF and the EI are illustrated by different cases by changing of the parameters of the WDO approach such as the friction coefficient, $\alpha$, the gravitational constant $g$, the velocity vector of the wind, $v$, the RT coefficient and the Coriolis constant, $c$.

The WDO approach is considered to have the capacity to get global solutions with stable convergence, and this is clear from the results obtained from all cases of simulations mentioned previously. Therefore, it can be recommended to future researchers as a promising this algorithm for solving some more complex engineering optimization problems. However, we have to mention that it becomes slow if the numbers of system variables are increased. It is found that the CPU time increases rapidly as system size increases (number of variables augmented) and the convergence slows down.

Finally, the result obtained by WDO approach is quite comparable with other methodology used for the OPF and EI problems.

| Methods       | Ref. | Cost ($/h) | Losses (MW) | Emission ($/ton) |
|---------------|------|------------|-------------|-----------------|
| Proposed      |      | 863.0300   | 8.9817      | 0.3106          |
| GA            | [3]  | 892.9601   | 7.705       | 0.2270          |
| ABC           | [23] | 820.1666   | 6.7244      | 0.2712          |
| PSO           | [23] | 822.0920   | -           | 0.2680          |
| MICA          | [87] | 865.0660   | 4.5703      | 0.2221          |
| MOGWO         | [3]  | 866.9852   | 5.3740      | 0.2229          |
|               | [88] | 833.8528   | -           | 0.2451          |

| Methods       | Ref. | Cost ($/h) | Losses (MW) | Emission ($/ton) |
|---------------|------|------------|-------------|-----------------|
| Proposed      |      | 863.0300   | 6.4499      | 0.1783          |
| GA            | [60] | 793.6054   | 8.4501      | 0.1878          |
| IABC          | [24] | 851.6111   | 4.8731      | 0.2230          |
| ABC           | [24] | 854.9166   | 4.9820      | 0.2280          |
| FAHSPSO-DE    | [86] | 867.9808   | 5.5638      | 0.2666          |

**Table 5** Comparison of obtained results for the cases 6 and 7 of IEEE 30-bus system.

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Conflict of interest
The Authors have no conflicts of interest to declare that they are relevant to the content of this article.

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Yes

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