Solving non-linear, non-smooth and non-convex optimal power flow problems using chaotic invasive weed optimization algorithms based on chaos

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ABSTRACT

Invasive Weed Optimization (IWO) algorithm is a simple but powerful algorithm which is capable of solving general multi-dimensional, linear and nonlinear optimization problems with appreciable efficiency. Recently IWO algorithm is being used in several engineering design owing to its superior performance in comparison with many other existing algorithms. This paper presents a Chaotic IWO (CIWO) algorithms based on chaos, and investigates its performance for optimal settings of Optimal Power Flow (OPF) control variables of OPF problem with non-smooth and non-convex generator fuel cost curves (non-smooth and non-convex OPF). The performance of CIWO algorithms are studied and evaluated on the standard IEEE 30-bus test system with different objective functions. The experimental results suggest that IWO algorithm holds immense promise to appear as an efficient and powerful algorithm for optimization in the power system.

1. Introduction

In the past two decades, an important tool for power system operators both in planning and operating stages is nonlinear OPF (Optimal Power Flow) problem and, OPF problem has established its position as one of the main tools for optimal operation of modern power systems. Main objective of the OPF problem is to optimize a chosen objective function such of generators fuel cost with non-smooth non-convex generator fuel cost curves by optimal adjusting the power system control variables and satisfying various system operating such as inequality constraints and power flow equations, simultaneously.

In general, the OPF problem is described as a large-scale highly constrained non-linear non-convex optimization problem in the power systems. Dommel and Tinney [1] were the first authors to introduce the formulation of the OPF problem for power system. The OPF problem has been solved via many traditional optimization methods such as Newton-based techniques, Quadratic Programming (QP), Interior Point Methods (IPM), Linear Programming (LP) and Non-Linear Programming (NLP) [2–5]. A comprehensive study of various optimization methods for OPF problem available in the literature is reported in Refs. [6,7]. However, these classical optimization methods are limited in handling algebraic functions and to provide the global minima and only reached the local one. Usually, these methods rely on the assumption that the fuel cost characteristic of a generating unit is a smooth, convex function. However, in some cases, the foregoing methods failed to represent the unit’s fuel cost characteristics as convex function such as solving nonlinear OPF problem by a predictor-corrector primal–dual log-barrier method as a sequence of linearized sub-problems on power systems of 118 and 1062 buses [5], a Decoupled Quadratic Load Flow (DQLF) solution with Enhanced Genetic Algorithm (EGA) algorithm to solve the multi-objective OPF problem for IEEE 30 bus system [8]. These situations arise when units prohibited operating zones, valve-points, and piece-wise quadratic cost characteristics are present. Therefore, there is a need for more robust and faster algorithm for OPF problem.

In recent years, many evolutionary optimization algorithms have been applied to solve complex constrained optimization problem which also include optimization problem in field of power systems. A wide variety of heuristic optimization algorithms have been applied such as Genetic Algorithm (GA) [9] based OPF problem for identifying the optimal values of generator active-power output and the angle of the phase-shifting transformer, Improved Genetic Algorithm (IGA) [10] to solve the OPF problem for both
Nomenclature

**Abbreviation**
- DEED: dynamic economic emission dispatch
- DED: dynamic economic dispatch
- DOPF: dynamic OPF
- DOPFP: distributed and parallel OPF
- DQLF: decoupled quadratic load flow
- ED: economic dispatch
- EED: environmental/economic dispatch
- IEEE: Institute of Electrical and Electronics Engineers
- MPRPV: multi-objective probabilistic reactive power and voltage control
- PMWTEED: probabilistic multi-objective wind-thermal economic dispatch
- UPFC: unified power flow controller
- VAR: volt amperes reactive

**Symbols**
- $a_i$, $b_i$, $c_i$, $d_i$, $e_i$: fuel cost coefficients of the $i$th generator unit
- $a_{ik}$, $b_{ik}$, $c_{ik}$: cost coefficients of the $i$th generator for fuel type $k$
- $B_{ij}$: susceptance of between bus $i$ and bus $j$ (p.u.)
- $F_i(P_{Gi})$: fuel cost of the $i$th generator ($$/h$)
- $G_{ij}$: conductance of between bus $i$ and bus $j$ (p.u.)
- $G_i$: $i$th generating unit
- $l$: lower bound of the prohibited zone of the generator
- $m_i$: number of prohibited zones in $i$th unit
- $NB$: number of buses
- $NC$: number of shunt VAR compensators
- $NG$: number of total generator
- $NPQ$: number of $PQ$ buses
- $NT$: number of transmission lines
- $NTL$: number of transmission lines
- $P_{Di}$: active load demand of $j$th bus (MW)
- $P_{Gi}$: generator active power output of generating $i$th unit (MW)
- $P_{Gmin}$: minimum active power output of $i$th generating unit
- $P_{Gmax}$: maximum active power output of $i$th generating unit
- $Q_{Di}$: reactive load demand of $j$th bus (MVAR)
- $Q_{Gi}$: generator reactive power output of $i$th generating unit (MVAR)
- $Q_{Gmin}$: minimum reactive power output of $i$th generating unit
- $Q_{Gmax}$: maximum reactive power output of $i$th generating unit
- $Q_{lim}$: minimum VAR injection limit of $i$th shunt compensator
- $Q_{lim}$: maximum VAR injection limit of $i$th shunt compensator
- $S_i$: maximum apparent power flow limit of $i$th branch
- $S_{ij}$: maximum apparent power flow limit of $i$th branch
- $T_i$: transformer taps settings of $i$th transformer (p.u.)
- $T_{jmin}$: minimum tap settings limit of $i$th transformer
- $T_{jmax}$: maximum tap settings limit of $i$th transformer
- $u$: upper bound of the prohibited zone of the generator
- $V_{Gi}$: generation bus voltages of $i$th generating unit (p.u.)
- $V_{lim}$: minimum generator voltage of $i$th generating unit
- $V_{lim}$: maximum generator voltage of $i$th generating unit
- $V_i$: voltage of $i$th bus (p.u.)
- $V_j$: voltage of $j$th bus (p.u.)
- $V_{Li}$: load voltage of $i$th bus
- $V_{Uj}$: limit value of the dependent variable $x$
- $X_{lim}$: maximum value of the dependent variable $x$
- $X_{lim}$: minimum value of the dependent variable $x$
- $\delta_{ij}$: phase difference of voltages between bus $i$ and bus $j$ (Rad)
- $\lambda_{P}$: penalty factors of active power generation of the slack bus
- $\lambda_{V}$: penalty factors of PQ bus voltage magnitudes
- $\lambda_{Q}$: penalty factors of reactive power output of the generator buses
- $\lambda$: penalty factors of transmission line loadings

**Abbreviation of algorithms**
- ACO: ant colony optimization
- BCO: bee colony optimization
- CIWO: chaotic invasive weed optimization
- COA: chaotic optimization algorithm
- CSS: charged system search
- DE: differential evolution
- EADDE: evolving ant direction differential evolution
- ECSS: enhanced charged system search
- EGA: enhanced genetic algorithm
- FCASO: fuzzy adaptive chaotic ant swarm optimization
- FFA: firefly algorithm
- FPSO: fuzzy evolutionary and particle swarm optimization
- GA: genetic algorithm
- ICA: imperialist competitive algorithm
- IGA: improved genetic algorithm
- IHS: improved harmony search
- IPM: interior point methods
- IWO: invasive weed optimization
- LP: linear programming
- MBSO: modified bee swarm optimization
- MHBMO: modified honey bee mating optimization
- MPSO: modified particle swarm optimization
- MPSO-SFLA: hybrid of MPSO and SFLA
- MSFLA: modified shufle frog leaping algorithm
- MTBLO: modified teaching–learning algorithm
- M.0-SBFAMulti-objective 0-smart bacterial foraging algorithm
- NLP: non-linear programming
- PSO: particle swarm optimization
- QP: quadratic programming
- SA: simulated annealing
- SFLA: shuffle frog leaping algorithm
- SQP: sequential quadratic programming
- TLA: teaching learning algorithm
- TS: tabu search

**Parameters of CIWO**
- $Cm$: chaotic variables
- $F_i$: goal value
- $F_{G_{best}}$: best goal value
- $F_{G_{worst}}$: worst goal value
- $iter_{max}$: maximum number of iterations algorithm
normal and contingent operation states, Tabu Search (TS) algorithm [11], which has been examined on the standard IEEE 30-bus power system with generator cost curves and different objectives of cost curves, and Simulated Annealing (SA) algorithm [12] to solve the OPF problem simultaneously composed by the economic dispatch problem and the load flow. In Ref. [13], attention is focused on the modeling and solution of a parameterized multi-objective OPF problem. Also, other heuristic optimization algorithms have been applied such as Particle Swarm Optimization (PSO) algorithm with different objectives that reflect fuel cost minimization, voltage stability enhancement, and voltage profile improvement to solve the OPF problem [14], a Modified Shuffle Frog Leaping Algorithm (MSFLA) for multi-objective OPF problem considers economical and emission issues [15], a simple yet efficient Harmony Search (HS) algorithm with a new pitch adjustment rule is proposed in the [16] for Dynamic Economic Dispatch (DED) problem of electrical power systems, a Modified Honey Bee Mating Optimization (MHBMO) algorithm considering generator constraints to solve the Dynamic OPF (DOPF) problem of power system [17], an Evolving Ant Direction Differential Evolution (EADDE) algorithm for solving the non-smooth and non-convex OPF problem [18], a novel hybrid algorithm based on the Shuffle Frog Leaping Algorithm (SFLA) and the Modified PSO (MPSO) Algorithms (MPSO-SFLA) [19] for solving the OPF problem considering generator constraints and multi-fuel type, fuzzy multi-objective PSO using multi-objective framework where in the total fuel cost and active power losses considering Unified Power Flow Controller (UPFC) [20], a proposed Distributed and Parallel OPF (DPOPF) algorithm for smart grid with renewable energy sources to minimizing the fuel cost and reduce carbon emission for energy saving in the OPF problem [21], Improved Harmony Search (IHS) algorithm [22] for smooth and non-smooth fuel—cost curve, the Enhanced Charged System Search (ECS) algorithm [23] which is a new method to solve the reserve constrained dynamic OPF applying to two small and large-scale case studies including 30 and 118 buses test systems, a new population-based optimization algorithm called Modified Teaching—Learning Algorithm (MTLBO) [24] which is proposed to determine the set of non-dominated optimal solutions for Probabilistic Multi-Objective Wind-Thermal Economic Emission Dispatch (PMWTEED) problem based on point estimated method, Charged System Search (CSS) algorithm [25] for Economic Power Dispatch (EPD) problem with prohibited operating zone which considers ramp rate limit, and a novel hybrid algorithm of Imperialist Competitive Algorithm (ICA) and Teaching—Learning Algorithm (TLA) for non-smooth OPF problem with non-smooth and non-convex generator fuel cost curves [26] have proved to be successful in solving nonlinear OPF problem in field of power systems with different objectives. In Ref. [27], a new analytical model is fostered to allocate losses to the line model in OPF and reveals that harmonics, even below the standard levels, have considerable effects on the overall value of energy trades. In Ref. [28], an interactive fuzzy satisfying method based on the novel Fuzzy Self-Adaptive Learning Particle Swarm Optimization (FSALPSO) approach is proposed for multi-objective Dynamic Economic Emission Dispatch (DEED) problem considering load and wind power uncertainties. A new multi-objective enhanced Firefly Algorithm (FFA) is proposed for solving Reserve Constrained Combined Heat and Power Dynamic Economic Emission Dispatch (RCCHPDEED) problem [29]. A hybrid algorithm integrating the Fuzzy Adaptive Chaotic Ant Swarm Optimization (FACASO) algorithm and the Sequential Quadratic Programming (SQP) techniques, named FACASO-SQP algorithm, is presented for solving the Dynamic Economic (ED) problems with valve-point effects [30] and [31] presents a new and efficient method using hybrid FFA method for solving EPD problem. In Refs. [32,33] proposed a Multi-Objective Probabilistic Reactive Power And Voltage Control (MPRPC) problem in distribution networks using wind turbines, hydro turbines, load tap changing transforms fuel cells, and static compensators.

Recently, chaotic sequences have been used in many applications such as DNA computing [34]; secure transmission [35], and nonlinear circuits [36]. The choice of chaotic sequences is justified theoretically by their unpredictability. Also, chaotic sequences have been used together with other algorithms such as Ant Colony Optimization (ACO) and Bee Colony Optimization (BCO) algorithms [37,38], PSO algorithm [39], ICA [40], SA algorithm [41], GA algorithms [42] and HS algorithm [43].

This paper presents CIWO (Chaotic IWO) algorithms for solving nonlinear non-convex and non-smooth OPF problem in the power system. IWO (Invasive Weed Optimization) algorithm which is used herein as the optimization algorithm of players is a new biologically motivated algorithm introduced by Mehrabian and Lucas [44] to solve optimization and control problems, which is inspired from weed colonization. IWO algorithm has found successful applications in many practical optimization problems like optimization and tuning of a developing a recommender system [45], U-array MIMO antenna design [46], design of encoding sequences for DNA computing [47], optimal reactive power dispatch problem [48], design of E-shaped MIMO Antenna [49], chaotic hybrid IWO algorithm using logistic, sinusoidal and tent maps is introduced to solving the constraints for solving the machinery optimizing problems [50], and optimal positioning of piezoelectric actuators [51]. The performance of this approach for nonlinear OPF problem with non-smooth cost functions such as fuel cost curves with valve point effects, fuel cost curves with prohibited zones, piecewise quadratic cost functions, is studied and evaluated on the standard IEEE 30-bus system.

The rest of this article is classified in four sections as follows: section 2 covers formulation of a nonlinear OPF problem while section 3 explains the standard structure of the CIWO algorithms and proposed hybrid method, section 4 of the paper is allocated to presenting optimization results and undertaking comparison and analysis of the performance of the mentioned methods used to

<table>
<thead>
<tr>
<th>Subscripts</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>N&lt;sub&gt;0&lt;/sub&gt;</td>
<td>seeds initial population</td>
</tr>
<tr>
<td>n</td>
<td>problem dimensional space</td>
</tr>
<tr>
<td>S&lt;sub&gt;i&lt;/sub&gt;</td>
<td>position of seed for the i&lt;sup&gt;th&lt;/sup&gt; plant</td>
</tr>
<tr>
<td>S&lt;sub&gt;max&lt;/sub&gt;</td>
<td>maximum number of seeds</td>
</tr>
<tr>
<td>S&lt;sub&gt;min&lt;/sub&gt;</td>
<td>minimum number of seeds for CIWO</td>
</tr>
<tr>
<td>W&lt;sub&gt;max&lt;/sub&gt;</td>
<td>maximum number of plants for CIWO</td>
</tr>
<tr>
<td>W&lt;sub&gt;i&lt;/sub&gt;</td>
<td>i&lt;sup&gt;th&lt;/sup&gt; weed plant</td>
</tr>
<tr>
<td>x&lt;sub&gt;k&lt;/sub&gt;</td>
<td>k&lt;sup&gt;th&lt;/sup&gt; chaotic number</td>
</tr>
<tr>
<td>δ&lt;sub&gt;start&lt;/sub&gt;</td>
<td>initial vale of standard deviation</td>
</tr>
<tr>
<td>δ&lt;sub&gt;stop&lt;/sub&gt;</td>
<td>final vale of standard deviation</td>
</tr>
<tr>
<td>λ</td>
<td>nonlinear modulation index</td>
</tr>
<tr>
<td>C</td>
<td>shunt compensator</td>
</tr>
<tr>
<td>D</td>
<td>load demand</td>
</tr>
<tr>
<td>G</td>
<td>generating unit</td>
</tr>
<tr>
<td>K</td>
<td>fuel type</td>
</tr>
<tr>
<td>L</td>
<td>load</td>
</tr>
<tr>
<td>I</td>
<td>line</td>
</tr>
<tr>
<td>P</td>
<td>active power</td>
</tr>
<tr>
<td>Q</td>
<td>reactive power</td>
</tr>
<tr>
<td>S</td>
<td>transmission line loadings</td>
</tr>
<tr>
<td>V</td>
<td>voltage</td>
</tr>
</tbody>
</table>
solve the case studies of nonlinear OPF problem on standard IEEE 30-bus system and finally, in section 5, the conclusion of the implementation for the hybrid method is presented.

2. OPF problem formulation

The main goal of OPF problem is to optimize a certain objective subject via optimal adjustments of power system control variables while satisfying various equality and inequality constraints, and can be written in the following form [11–14]:

\[
\text{Min } J(x, u) \\
\text{Subject to : } g(x, u) = 0 \quad (1) \\
h(x, u) \leq 0 \quad (2)
\]

where \( J \) is the objective function to be minimized and vector \( x \) denotes the state variables of a power system network that contains:

1. Generator active power output at slack bus \( (P_{G1}) \).
2. Load bus voltage.
3. Generator reactive power output.
4. Transmission line loading (or line flow).

Accordingly, the \( x \) vector can be illustrated as the following:

\[
x^T = [P_{G1}, V_{L1}..., V_{LNPQ}, Q_{G1}..., Q_{GNG}, S_{N1}..., S_{NTL}] \\
\]

\( u \) is the vector of independent (control) variables consisting of:

1. Generator active bus voltages.
2. Generator active power output at PV buses except at the slack bus.
3. Transformer taps settings.

Therefore, \( u \) is the vector of control variables can be expressed as:

\[
u^T = [P_{G2}..., P_{GNG}, V_{G1}..., V_{GNG}, Q_{C1}..., Q_{CN}, T_1..., T_{NT}] \\
\]

2.1. Constraints

2.1.1. Equality constraints

\( g(x, u) \) is the equality constraints in the OPF problem. These constraints reflect the physics of the power system, which are given below [1]:

\[
P_{Gi} - P_{Di} - \sum_{j=1}^{NB} V_j \left[ G_{ij} \cos(\delta_i - \delta_j) + B_{ij} \sin(\delta_i - \delta_j) \right] = 0 \\
Q_{Gi} - Q_{Di} - \sum_{j=1}^{NB} V_j \left[ G_{ij} \sin(\delta_i - \delta_j) - B_{ij} \cos(\delta_i - \delta_j) \right] = 0
\]

2.1.2. Inequality constraints

\( h(x, u) \) is the inequality constraints that include:

i. Generator related constraints: generation bus voltages, active power outputs, and reactive power outputs are restricted by their lower and upper limits as:

\[
\begin{align*}
V_{G1}^{\text{min}} & \leq V_{Gi} \leq V_{G1}^{\text{max}}, & i = 1, ..., NG \\
P_{G1}^{\text{min}} & \leq P_{Gi} \leq P_{G1}^{\text{max}}, & i = 1, ..., NG \\
Q_{G1}^{\text{min}} & \leq Q_{Gi} \leq Q_{G1}^{\text{max}}, & i = 1, ..., NG
\end{align*}
\]

ii. Transformer limitations: transformer tap settings are restricted by their lower and upper limits as:

\[
T_i^{\text{min}} \leq T_i \leq T_i^{\text{max}}, & i = 1, ..., NT
\]

Shunt VAR (Volt Amperes Reactive) compensator constraints: shunt VAR compensations are restricted by their limits as:

\[
Q_{Ci}^{\text{min}} \leq Q_{Ci} \leq Q_{Ci}^{\text{max}}, & i = 1, ..., NC
\]

Fig. 1. Flowchart showing the working of algorithms for OPF problems.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>start</td>
<td>40</td>
</tr>
<tr>
<td>T1max</td>
<td>100</td>
</tr>
<tr>
<td>Wmax</td>
<td>80</td>
</tr>
<tr>
<td>Nmax</td>
<td>15</td>
</tr>
<tr>
<td>Nmin</td>
<td>3</td>
</tr>
<tr>
<td>j</td>
<td>3</td>
</tr>
<tr>
<td>bhalt</td>
<td>10</td>
</tr>
<tr>
<td>bstop</td>
<td>1</td>
</tr>
</tbody>
</table>
iii. Security constraints: include the constraints of voltages at load buses and transmission line loading as:

\[
V_{Li}^{\min} \leq V_{Li} \leq V_{Li}^{\max}, \quad i = 1, \ldots, NPQ
\]

\[
S_{Li} \leq S_{Li}^{\max}, \quad i = 1, \ldots, NTL
\]

In the most of the nonlinear optimization problems in the power systems, the constraints are considered by generalizing the

\[
S_{Li} \leq S_{Li}^{\max}, \quad i = 1, \ldots, NTL
\]

Table 2
Generator cost coefficients and zones for OPF problems 1, 2 and 3.

<table>
<thead>
<tr>
<th>Generator number</th>
<th>(a)</th>
<th>(b)</th>
<th>(c)</th>
<th>(d)</th>
<th>(e)</th>
<th>(P_{G_i}^{\max}) (MW)</th>
<th>(P_{G_i}^{\min}) (MW)</th>
<th>Prohibit zones</th>
</tr>
</thead>
<tbody>
<tr>
<td>(G_1)</td>
<td>0.0</td>
<td>2</td>
<td>0.00375</td>
<td>18</td>
<td>0.037</td>
<td>250</td>
<td>50</td>
<td>[55–66], [80–120]</td>
</tr>
<tr>
<td>(G_2)</td>
<td>0.0</td>
<td>1.75</td>
<td>0.0175</td>
<td>16</td>
<td>0.038</td>
<td>80</td>
<td>20</td>
<td>[21–24], [45–55]</td>
</tr>
<tr>
<td>(G_3)</td>
<td>0.0</td>
<td>1.0</td>
<td>0.0025</td>
<td>14</td>
<td>0.04</td>
<td>50</td>
<td>15</td>
<td>[30–36]</td>
</tr>
<tr>
<td>(G_6)</td>
<td>0.0</td>
<td>3.25</td>
<td>0.00834</td>
<td>12</td>
<td>0.045</td>
<td>35</td>
<td>10</td>
<td>[25–30]</td>
</tr>
<tr>
<td>(G_{11})</td>
<td>0.0</td>
<td>3</td>
<td>0.025</td>
<td>13</td>
<td>0.042</td>
<td>30</td>
<td>10</td>
<td>[25–28]</td>
</tr>
<tr>
<td>(G_{13})</td>
<td>0.0</td>
<td>3</td>
<td>0.025</td>
<td>13.5</td>
<td>0.041</td>
<td>40</td>
<td>12</td>
<td>[24–30]</td>
</tr>
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</table>

Table 3
Comparison of the best simulation results for problem 1.

<table>
<thead>
<tr>
<th>Method</th>
<th>(P_{G_1}) (MW)</th>
<th>(P_{G_2}) (MW)</th>
<th>(P_{G_3}) (MW)</th>
<th>(P_{G_4}) (MW)</th>
<th>(P_{G_5}) (MW)</th>
<th>(P_{G_6}) (MW)</th>
<th>(P_{G_{11}}) (MW)</th>
<th>(P_{G_{13}}) (MW)</th>
<th>Losses (MW)</th>
<th>Cost ($/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original</td>
<td>190.454</td>
<td>49.82</td>
<td>20.47</td>
<td>10.42</td>
<td>10.1</td>
<td>12.031</td>
<td>9.895</td>
<td>801.5425</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gauss/mouse map</td>
<td>189.358</td>
<td>49.222</td>
<td>18.605</td>
<td>12.305</td>
<td>11.427</td>
<td>12.012</td>
<td>9.529</td>
<td>800.3971</td>
<td></td>
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</tr>
<tr>
<td>Liebovitch map</td>
<td>192.125</td>
<td>48.786</td>
<td>19.636</td>
<td>10.384</td>
<td>10</td>
<td>12</td>
<td>9.531</td>
<td>801.1784</td>
<td></td>
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</tr>
<tr>
<td>Logistic map</td>
<td>188.062</td>
<td>49.604</td>
<td>20.022</td>
<td>13.524</td>
<td>10</td>
<td>12</td>
<td>9.812</td>
<td>801.2736</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intermittency map</td>
<td>191.486</td>
<td>47.353</td>
<td>19.365</td>
<td>12.728</td>
<td>10</td>
<td>12</td>
<td>9.532</td>
<td>800.2007</td>
<td></td>
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<tr>
<td>Iterative map</td>
<td>185.332</td>
<td>48.119</td>
<td>20.378</td>
<td>17.275</td>
<td>10</td>
<td>12</td>
<td>9.705</td>
<td>801.2654</td>
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<tr>
<td>Chebyshev map</td>
<td>193.751</td>
<td>46.246</td>
<td>19.537</td>
<td>11.319</td>
<td>10</td>
<td>12</td>
<td>9.453</td>
<td>799.9807</td>
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<tr>
<td>Circle map</td>
<td>187.85</td>
<td>46.933</td>
<td>18.662</td>
<td>15.028</td>
<td>12.435</td>
<td>12</td>
<td>9.508</td>
<td>800.6328</td>
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<td></td>
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<tr>
<td>Singer map</td>
<td>190.246</td>
<td>48.867</td>
<td>20.091</td>
<td>11.82</td>
<td>10.271</td>
<td>12</td>
<td>9.895</td>
<td>801.4743</td>
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<tr>
<td>Sinusoidal map</td>
<td>190.182</td>
<td>49.57</td>
<td>19.669</td>
<td>11.88</td>
<td>10</td>
<td>12</td>
<td>9.901</td>
<td>801.4821</td>
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<tr>
<td>Tent map</td>
<td>189.618</td>
<td>50.442</td>
<td>19.222</td>
<td>11.843</td>
<td>10.02</td>
<td>12</td>
<td>9.745</td>
<td>801.0119</td>
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</tbody>
</table>
objective function using penalty terms. In OPF problem, by adding penalty functions of the active power generation of the slack bus, PQ bus voltage magnitude, reactive power generation and transmission line loading to the objective function in (1). Therefore, the objective function can be augmented as follows [22,26]:

\[
J = \sum_{i=1}^{NG} F_i(P_{Gi}) + \lambda_P \left( P_{Gi} - P_{Gi}^{\text{lim}} \right)^2 + \lambda_V \sum_{i=1}^{NPQ} \left( V_{li} - V_{li}^{\text{lim}} \right)^2 + \lambda_Q \sum_{i=1}^{NPQ} \left( Q_{Gi} - Q_{Gi}^{\text{lim}} \right)^2 + \lambda_S \sum_{i=1}^{NTL} \left( S_{li} - S_{li}^{\text{lim}} \right)^2
\]  

(13)

\[x^{\text{lim}} \text{ is the limit value of the dependent variable } x \text{ and given as:}
\]

\[
x^{\text{lim}} = \begin{cases} 
  x; & x_{\min} < x < x_{\max} \\
  x_{\max}; & x \geq x_{\max} \\
  x_{\min}; & x \leq x_{\min} 
\end{cases}
\]

(14)

3. CIWO algorithm

3.1. IWO algorithm

One of the population based optimization algorithms which is inspired by colonial behavior of weeds, first introduced by Mehrabian and Locus, is IWO algorithm [44]. The IWO algorithm is a very simple and yet effective algorithm in determining optimal point of the objective function, which is developed on the basis of natural and basic features of weeds in a colony such as reproduction, growth and struggle to survive. In comparison to other algorithms, IWO is simpler and has appropriate capability and convergence rate to the global optimal point of objective function. Some of the primary characteristics of this algorithm which distinguishes it from other approaches are reproduction, space distribution and exclusive competition. The results of comparison between IWO, Shuffle Frog Leaping Algorithm (SFLA) and PSO indicate IWO’s competitive and even at some points, better performance relative to the mentioned approaches [44].

In order to simulate behavior of a weed, the following steps are arranged according to [51]:

Step 1: Initial population production: a population of \( N_0 \) seeds is randomly distributed in an \( n \) dimensional space.

Step 2: Reproduction: each seed grows and turns into a mature plant and then, begins seed production for newer generation. The amount of seeds produced by a plant increases linearly between two possible values of minimum and maximum possible amounts of produced seeds. The amount of produced seeds for the \( i \)th plant in every repeat is dependent to its goal value (\( F_i \)), its best (\( F^*_i \)) and worst (\( F^*_w \)) goal values in that repeat and is calculated with the following relation:

\[
\text{Fig. 3. Convergence of CIWO algorithms for problem 1.}
\]

\[
\text{Fig. 4. Cost function with and without valve point effect of the } i \text{th generating unit.}
\]
\[ num_{seeds}(t) = \frac{R_u - R_d}{R_d - R_u} (S_{\text{max}} - S_{\text{min}}) + S_{\text{min}} \]  

(15)

Step 3: Distribution space: the randomness and assimilation of the algorithm is related to this stage. The produced seeds are distributed in the n-dimensional search space with normal distribution which has zero mean and different variance of \( N(0, \delta_{\text{iter}})^n \). In this state, the seeds will be near the breeder plant. Although the standard deviation decreases from initial amount to final amount in each repeat, in the simulations, non-linear variation of standard deviation causes satisfactory results which are illustrated below:

\[ \delta_{\text{iter}} = \left( \frac{\text{iter}_{\text{max}} - \text{iter}}{\text{iter}_{\text{max}}} \right) ^\lambda * (\delta_{\text{start}} - \delta_{\text{stop}}) + \delta_{\text{stop}} \]  

(16)

In this status, the positions of seeds for the ith plant are calculated as follows:

\[ s_j = W_i + N(0, \delta_{\text{iter}})^n, 1 \leq j \leq \text{num}_{seeds}(t) \]  

(17)

Step 4: Exclusive competition: by several repeats, the number of plants produced by rapid reproduction reaches its maximum value, in this situation; every plant is permitted to produce seeds by in accordance with reproduction method. The seeds are authorized to spread in search space with correspondence to distribution space method, when the seeds find their position; they form a colony alongside their parent plants. Then members with less propriety are deleted in order to number of members reach its maximum allowed value. In this method, the parent plants combine with their children and the plants with most propriety from the group are preserved and allowed for replacement. This crowd control mechanism will be imposed on next generations until reaching the final period.

### 3.2. Chaos maps (or its adjective “chaotic”)

Currently, chaos has raised enormous interest in different fields of sciences especially heuristic optimization which needs random sequences with a long period and good uniformity. Chaos as a kind of dynamic behavior of nonlinear systems has a very sensitive dependence upon its initial condition and parameter. The nature of chaos is apparently random and unpredictable, and mathematically, it is randomness of a simple deterministic dynamical system and can be considered as sources of randomness [52,53].

The random-based optimization algorithms which use chaotic variables are called Chaotic Optimization Algorithm (COA). The COA technologies can accomplish overall searches at higher speeds than stochastic searches that depend on probabilities, due to the non-repetition and periodicity of chaos [53]. Some of the well-known one-dimensional maps are reviewed in following subsections:

#### 3.2.1. Gauss/mouse map

In mathematics, the Gauss map [46] is a nonlinear iterated map of the reals into a real interval given by the Gaussian function which can be defined with following equations:

\[ x_{k+1} = \begin{cases} \alpha x_k & \text{if } 0 < x_k \leq P_1 \\ \frac{P - x_k}{P_2 - P_1} & \text{if } P_1 < x_k \leq P_2 \\ 1 - \beta(1 - x_k) & \text{if } P_2 < x_k \leq 1 \end{cases} \]

(20)

In this equation \( \alpha < \beta \) and they are defined as:

\[ \alpha = \frac{P_2}{P_1}(1 - (P_2 - P_1)) \]

(21)

\[ \beta = \frac{1}{P_2 - 1}((P_2 - 1) - P_1(P_2 - P_1)) \]

(22)

Here three equal limits are considered for this map.

#### 3.2.2. Liebovitch map

Liebovitch and Toth introduce the map which can be formulated as follows [54]:

\[ x_{k+1} = \begin{cases} \alpha x_k & \text{if } 0 < x_k \leq P_1 \\ \frac{P - x_k}{P_2 - P_1} & \text{if } P_1 < x_k \leq P_2 \\ 1 - \beta(1 - x_k) & \text{if } P_2 < x_k \leq 1 \end{cases} \]

(20)

In this equation \( \alpha < \beta \) and they are defined as:

\[ \alpha = \frac{P_2}{P_1}(1 - (P_2 - P_1)) \]

(21)

\[ \beta = \frac{1}{P_2 - 1}((P_2 - 1) - P_1(P_2 - P_1)) \]

(22)

Here three equal limits are considered for this map.

#### 3.2.3. Logistic map

The logistic map [55] is a polynomial mapping of degree 2 which can arise from very simple non-linear dynamical equations. The Logistic map is represented by the following equation which appears in nonlinear dynamics of biological population evidencing chaotic behavior. The map was first introduced by Robert May in 1976.

<table>
<thead>
<tr>
<th>Method</th>
<th>( P_{10} ) (MW)</th>
<th>( P_{15} ) (MW)</th>
<th>( P_{10} ) (MW)</th>
<th>( P_{15} ) (MW)</th>
<th>( P_{10} ) (MW)</th>
<th>( P_{15} ) (MW)</th>
<th>Losses (MW)</th>
<th>Cost ($/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original</td>
<td>219.817</td>
<td>28.524</td>
<td>15.517</td>
<td>10</td>
<td>10</td>
<td>12</td>
<td>12.458</td>
<td>826.3698</td>
</tr>
<tr>
<td>Gauss/mouse map</td>
<td>219.816</td>
<td>28.579</td>
<td>15</td>
<td>10</td>
<td>10</td>
<td>12</td>
<td>11.995</td>
<td>824.7538</td>
</tr>
<tr>
<td>Liebovitch map</td>
<td>219.815</td>
<td>28.557</td>
<td>15</td>
<td>10</td>
<td>10</td>
<td>12</td>
<td>12.34</td>
<td>825.905</td>
</tr>
<tr>
<td>Logistic map</td>
<td>219.816</td>
<td>28.924</td>
<td>15</td>
<td>10</td>
<td>10</td>
<td>12</td>
<td>11.972</td>
<td>824.6794</td>
</tr>
<tr>
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<td>28.358</td>
<td>15.199</td>
<td>10</td>
<td>10</td>
<td>12</td>
<td>11.973</td>
<td>824.7074</td>
</tr>
<tr>
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<td>28.926</td>
<td>15</td>
<td>10</td>
<td>10</td>
<td>12</td>
<td>12.342</td>
<td>825.9117</td>
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<td>28.546</td>
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<td>10</td>
<td>10</td>
<td>12</td>
<td>11.962</td>
<td>824.6461</td>
</tr>
<tr>
<td>Circle map</td>
<td>219.816</td>
<td>28.592</td>
<td>15</td>
<td>10</td>
<td>10</td>
<td>12</td>
<td>12.008</td>
<td>824.7991</td>
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<tr>
<td>Piecewise map</td>
<td>219.816</td>
<td>28.528</td>
<td>15.071</td>
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<td>10</td>
<td>12</td>
<td>12.015</td>
<td>824.8304</td>
</tr>
<tr>
<td>Sine map</td>
<td>219.816</td>
<td>28.579</td>
<td>15</td>
<td>10</td>
<td>10</td>
<td>12</td>
<td>11.995</td>
<td>824.7538</td>
</tr>
<tr>
<td>Singer map</td>
<td>219.807</td>
<td>28.641</td>
<td>15.369</td>
<td>10</td>
<td>10</td>
<td>12</td>
<td>12.417</td>
<td>826.211</td>
</tr>
<tr>
<td>Sinusoidal map</td>
<td>219.816</td>
<td>28.186</td>
<td>15</td>
<td>10</td>
<td>10</td>
<td>12</td>
<td>12.602</td>
<td>826.7799</td>
</tr>
<tr>
<td>Tent map</td>
<td>219.816</td>
<td>28.35</td>
<td>15.541</td>
<td>10</td>
<td>10</td>
<td>12</td>
<td>12.307</td>
<td>825.8714</td>
</tr>
<tr>
<td>Hybrid</td>
<td>219.816</td>
<td>28.466</td>
<td>15</td>
<td>10</td>
<td>10</td>
<td>12</td>
<td>11.882</td>
<td>824.3801</td>
</tr>
</tbody>
</table>
\[ x_{k+1} = \alpha x_k (1 - x_k) \]  

(23)

In Eq. (23), \( x_k \) is the \( k \)th chaotic number, with \( k \) denoting the iteration number. Obviously, \( x \in (0, 1) \) under the conditions that the initial \( x_0 \in (0, 1) \) and that \( x_0 \neq \{0.0, 0.25, 0.75, 0.5, 1.0\} \). In the experiments \( \alpha = 4 \) is used in this paper.

3.2.4. Intermittency map

The intermittency map [56] is composed of two parts, one of them is linear and another one is non-linear. It is formulated as follows:

\[
x_{k+1} = \begin{cases} 
\epsilon + x_k + \alpha x_k^0 & 0 < x_k \leq P \\
\frac{x_k - P}{1 - P} & P < x_k \leq 1
\end{cases}
\]  

(24)

3.2.5. Iterative map

The iterative chaotic map [55] with infinite collapses can be written as follows:

\[
x_{k+1} = \sin \left( \frac{\alpha \pi}{x_k} \right)
\]  

(25)

In Eq. (25), \( \alpha \in (0, 1) \) is a suitable parameter.

3.2.6. Chebyshev map

The family of Chebyshev map [54] is defined as follows:

\[
x_{k+1} = \cos \left( k \cos^{-1}(x_k) \right)
\]  

(26)

3.2.7. Circle map

The Circle map [57] is defined as follows:

\[
x_{k+1} = x_k + \beta - (\alpha/2\pi) \sin(2\pi x_k) \text{mod}(1)
\]  

(27)

With \( \alpha = 0.5 \) and \( \beta = 0.2 \), chaotic sequence is generated in \((0, 1)\).

3.2.8. Piecewise map

The piecewise map [58] can be written as follows:

\[
x_{k+1} = \begin{cases} 
\frac{x_k}{P} & 0 \leq x_k < P \\
\frac{x_k - P}{0.5 - P} & P \leq x_k < 0.5 \\
\frac{1 - P - x_k}{0.5 - P} & 0.5 \leq x_k < 1 - P \\
\frac{1 - x_k}{P} & 1 - P \leq x_k < 1
\end{cases}
\]  

(28)

In Eq. (28), \( P \) is the control parameter between 0 and 0.5, and \( x \in (0, 1) \).

3.2.9. Sine map

The sine map [59] is a unimodal map and is defined as follows:

\[
x_{k+1} = x_k + \beta - (\alpha/2\pi) \sin(2\pi x_k) \text{mod}(1)
\]  

(29)

With \( \alpha = 0.5 \) and \( \beta = 0.2 \), chaotic sequence is generated in \((0, 1)\).
where μ is a control parameter, and is between 0.9 and 1.08.

3.3. CIWO

New algorithms called chaotic algorithms can be created by using chaotic behavior [63–65]. Trapping in local optima is one of the major drawbacks of IWO algorithm. But, escaping from local optima is the main characteristic of chaotic algorithms. Also, another important feature of chaotic algorithms is their lower sensitivity to initial values than other algorithms. In this paper, the chaotic behavior is modeled as a quadratic function. The values of cost coefficients for various kinds of these variables. By using Eq. (32), parent plant is allowed with different approaches to naturally produce seeds.

\[ S_j = w_l + \delta_{iter} \ast cm_j \]  

(34)

3.4. Proposed hybrid method

In IWO algorithm, each parent plant individually produces seeds in their colony. In consequence, there will be less searching in some area especially between parent plants. In the proposed hybrid approach, using powerful and effective DE/best/2/bin algorithm [66,67] and Chebyshev map (map strongest in simulation), the IWO algorithm is allowed to exchange and cooperate between the various colonies. This procedure is defined in Eq. 35:

\[ S_j = \begin{cases} w_l + \delta_{iter} \ast cm_j & \text{if } rand_i(0,1) < 0.5 \\ w_{strongest} + cm_j(w_l - w_{ii}) + cm_j(w_{ii} - w_l) & \text{otherwise} \end{cases} \]  

(35)

This equation is used instead of Eq. (17). In this equation, four various parent plants is randomly selected with the powerful parent plant in all colonies, and they perform seeds production. Fig. 1 shows the flowchart of CIWO algorithms for optimization problem of power system.

4. Simulation results

In order to demonstrate the robustness, performance and efficiency of the proposed CIWO algorithms are tested for solving IEEE 30 bus power system. The proposed algorithms have been implemented in MATLAB 7.6 and the simulation run on a Pentium IV E5200 PC 2 GB RAM.

Penalty factors in (13) for all the test systems are chosen, \( \lambda_P = 50,000,000, \lambda_Q = 50,000 \) and \( \lambda_S = 1000 \). In each case, 30 test runs were performed for solving the OPF problem using the proposed algorithms. The proposed algorithms parameters used for the simulation are summarized in Table 1.

The IEEE 30-bus test system has 6 generators at the buses 1, 2, 5, 8, 11 and 13 and four transformers with off-nominal tap ratio at lines 6–9, 6–10, 4–12 and 28–27 and two capacitor banks at buses 5 and 24. Fig. 2 shows the one-line diagram of a standard IEEE 30-bus test system. The system data and cost coefficients with valve-point effects and prohibited zones are taken from Refs. [68–70]. The total system demand is 2.834 p.u. at 100 MVA base. The limit voltages of all load buses are considered to be 1.05–0.95 in p.u.

4.1. Problem 1: minimization of fuel cost

In this OPF problem, the fuel cost curve for all generators is modeled as a quadratic function. The values of cost coefficients for this problem are presented in Refs. [68,69] and are presented in Table 5.

<table>
<thead>
<tr>
<th>Method</th>
<th>( P_{C1} ) (MW)</th>
<th>( P_{C2} ) (MW)</th>
<th>( P_{C3} ) (MW)</th>
<th>( P_{C4} ) (MW)</th>
<th>( P_{C5} ) (MW)</th>
<th>( P_{C6} ) (MW)</th>
<th>( P_{C7} ) (MW)</th>
<th>( P_{C8} ) (MW)</th>
<th>( P_{C9} ) (MW)</th>
<th>( P_{C10} ) (MW)</th>
<th>( P_{C11} ) (MW)</th>
<th>( P_{C12} ) (MW)</th>
<th>Losses (MW)</th>
<th>Cost ($/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original</td>
<td>196.143</td>
<td>45</td>
<td>20.094</td>
<td>10</td>
<td>10</td>
<td>12.125</td>
<td>9.962</td>
<td>801.9577</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intermittency map</td>
<td>194.248</td>
<td>45</td>
<td>19.597</td>
<td>12.486</td>
<td>10</td>
<td>12</td>
<td>9.802</td>
<td>801.6241</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Iterative map</td>
<td>194.267</td>
<td>45</td>
<td>19.635</td>
<td>12.415</td>
<td>10</td>
<td>12</td>
<td>9.961</td>
<td>801.8658</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chebyshev map</td>
<td>194.366</td>
<td>45</td>
<td>19.609</td>
<td>13.197</td>
<td>12</td>
<td>9.983</td>
<td>801.5969</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Circle map</td>
<td>194.322</td>
<td>45</td>
<td>19.659</td>
<td>12.369</td>
<td>12</td>
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</tr>
<tr>
<td>Piecewise map</td>
<td>194.422</td>
<td>45</td>
<td>19.65</td>
<td>12.322</td>
<td>10</td>
<td>12</td>
<td>9.889</td>
<td>801.632</td>
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<tr>
<td>Tent map</td>
<td>194.075</td>
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<td>12.689</td>
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<td>9.951</td>
<td>801.8255</td>
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<td>Hybrid</td>
<td>193.482</td>
<td>45</td>
<td>19.807</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 2. The objective function of this problem can be formulated as follows:

\[
J = \sum_{i=1}^{NG} F_i(P_{Gi}) = \sum_{i=1}^{NG} \left( a_i + b_iP_{Gi} + c_iP_{Gi}^2 \right) 
\]

The best values of the 30 runs from proposed algorithms are presented in Table 3; the proposed hybrid method is giving better quality solution. The fuel cost obtained by the proposed hybrid method is found to be less than other CIWO algorithms results. Fig. 3 shows the steep convergence of best individual solution's generation cost against the number of generations of proposed algorithms.

4.2. Problem 2: minimization of fuel cost with considering the valve point effect

In this OPF problem, the fuel cost function of the generator is modeled as a quadratic with rectified sinusoidal terms to account for the valve-point loading effects. Its objective function can be described as follows:

\[
J = \sum_{i=1}^{NG} \left( a_i + b_iP_{Gi} + c_iP_{Gi}^2 + d_i \sin \left( e_i \left( P_{\min Gi} - P_{Gi} \right) \right) \right) 
\]

Owing to the addition of sinusoidal terms, the function becomes non-convex and challenges the gradient-based proposed CIWO algorithms. Fig. 4 [26] shows the cost function of generators without and with the valve point effect of the i-th generating unit.

The fuel cost coefficients for these units for problem 2 are presented in Table 2. Table 4 shows the comparison of the proposed hybrid method with other CIWO algorithms. According to the obtained solutions for each method, the minimum cost obtained from the proposed hybrid method is 824.3801 $/h, it is found that the hybrid method is giving better solution than the other CIWO algorithms. Fig. 5 shows the convergence of the CIWO algorithms for the cost function for problem 2 of study. As can been seen, the ability of the offered proposed CIWO algorithms to find accurate OPF solutions, in problem 2 of study is reinstated by the gathered results.

4.3. Problem 3: minimization of fuel cost with considering the prohibited zones

The prohibited operating zones in the unit's strictly limit the unit's ability for regulating system load. Load regulation can
result in falling into certain prohibited operating zones. Therefore, in the practice when adjusting the operation output of a unit one must avoid the operation in the prohibited zones [26].

Table 2 presents the fuel cost coefficients and prohibited for all generators units of problem 3. The objective function of this problem is minimization of fuel cost with considering the prohibited zones for all generators which can be formulated as follows:

$$\begin{align*}
P_{\min}^{G_i} & \leq P_{G_i} \leq P_{\max}^{G_i} \\
P_{G_{ij}}^{G_i} - 1 & \leq P_{G_i} \leq P_{G_{ij}}^\text{max} \\
P_{G_{in}}^{G_i} - 1 & \leq P_{G_i} \leq P_{G_{in}}^\text{max} 
\end{align*}$$

(38)

Fig. 6 [26] shows the fuel cost function with prohibited zones for solving IEEE 30 bus power system.

The best results obtained of fuel cost by original IWO and CIWO algorithms are compared in Table 5. Judging from Table 5,

<table>
<thead>
<tr>
<th>Method</th>
<th>$P_{G1}$ (MW)</th>
<th>$P_{G2}$ (MW)</th>
<th>$P_{G5}$ (MW)</th>
<th>$P_{G11}$ (MW)</th>
<th>$P_{G13}$ (MW)</th>
<th>Losses (MW)</th>
<th>Cost ($/h$)</th>
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<tbody>
<tr>
<td>Gauss/mouse map</td>
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<td>55</td>
<td>23.977</td>
<td>34.89</td>
<td>18.412</td>
<td>18.008</td>
<td>6.887</td>
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<td>55</td>
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<td>18.866</td>
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<td>18.512</td>
<td>19.759</td>
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<td>16.904</td>
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<td>24.478</td>
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<td>18.263</td>
<td>17.497</td>
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<td>Circle map</td>
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<td>55</td>
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<td>34.999</td>
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<td>55</td>
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<td>34.997</td>
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<td>17.57</td>
<td>6.87</td>
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<tr>
<td>Sinusoidal map</td>
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<td>23.013</td>
<td>30.443</td>
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<tr>
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<td>34.999</td>
<td>19.141</td>
<td>17.253</td>
<td>6.835</td>
</tr>
</tbody>
</table>
it can be seen that the minimum cost using hybrid method is 800.4735 $/h which is less in comparison to the best results obtained using original IWO and CIWO algorithms. This demonstrates the effectiveness of the CIWO algorithms to solve nonlinear OPF problem. Also the convergence for the minimum fuel cost with considering the prohibited zones of proposed algorithms is shown in Fig. 7.

4.4. Problem 4: minimization of fuel cost with considering different fuel types

In practical power system, many thermal generating units may be supplied with several fuel sources like oil, coal or natural gas. The fuel cost functions of these units may be disassembled as piecewise quadratic fuel cost functions for different fuel types [70]. The optimization problem becomes a non-convex OPF problem with discontinuous values at each boundary. Fig. 8 shows cost function curve related to the different fuel types, and also fuel cost coefficients for these units are presented in Table 6.

Clearl, the fuel cost coefficients of remaining single fuel source generators have the same values as problem 1 condition. The fuel cost characteristics for the generating units connected at number 1 and 2 buses are now represented by a piecewise quadratic function to model different fuels given by Ref. [70]:

\[
F(P_{Gi}) = \left\{ \begin{array}{ll}
\alpha_{i1} + b_1 P_{Gi} + c_i P_{Gi}^2 & p_{Gi}^\text{min} \leq P_{Gi} \leq p_{Gi1} \\
\alpha_{i2} + b_2 P_{Gi} + c_i P_{Gi}^2 & p_{Gi1} \leq P_{Gi} \leq p_{Gi2} \\
\alpha_{ik} + b_k P_{Gi} + c_i P_{Gi}^2 & P_{Gi-k-1} \leq P_{Gi} \leq p_{Gi}^\text{max}
\end{array} \right.
\]  

(39)

Objective function can be described as [70]:

\[
J = \left( \frac{1}{2} \sum_{i=1}^{NG} a_{ik} + b_i P_{Gi} + c_i P_{Gi}^2 \right) + \left( \frac{1}{3} \sum_{i=3}^{NG} a_{i3} + b_i P_{Gi} + c_i P_{Gi}^2 \right)
\]

(40)

To assess the potential of the proposed approach, a comparison between the results of fuel cost obtained by the hybrid method with original IWO and CIWO algorithms are shown in Table 7. According to the obtained simulation of algorithms, it can be seen that the minimum fuel cost is 646.8707 $/h using hybrid method, which is less in comparison with the other algorithms. The fast convergence of total fuel cost with considering different fuel types using all algorithms are shown in Fig. 9. The results confirm the potential of the proposed CIWO algorithms to handle non-smooth OPF and non-convex OPF problems in the power system.

The critical performance indexes such as the best (minimum) cost (best), the worst (maximum) cost (worst), the standard deviation (std) and the mean cost (mean) for test power system using all algorithms for 30 independent runs are shown in Table 8. According to the presented results, the proposed algorithms were successfully implemented to find global or near global optimal settings of the control variables of the IEEE 30-bus power system.

As can be seen from Table 8, the statistical results of the hybrid method are better than those of original IWO and CIWO algorithms.

5. Conclusions

In this paper, chaotic invasive weed optimization algorithms have been offered as novel chaotic algorithms for solving non-smooth and non-convex optimal power flow in standard IEEE 30-bus power system.
bus power system. The OPF problem is a large scale highly constrained nonlinear non-convex optimization problem with equality and inequality constraints in power systems. During the study, different non-smooth and non-convex cost functions were considered to minimize the fuel cost such as quadratic fuel cost function, fuel cost function with valve point effect, and fuel cost function with considering the prohibited zones. From the simulation results and comparison, the proposed novel chaotic algorithms are able to produce the high-quality solutions for different objectives of OPF problem. The proposed novel chaotic algorithms are able to reach a better optimal solution than original IWO algorithm. It is also found proposed novel chaotic algorithms are more suitable for non-linear OPF problem with non-smooth and non-convex cost functions.

References


[38] Lin SY, Chen JF. Distributed optimal power flow for smart grid transmission system with renewable energy sources. Energy 2013;56:184–9212.


