Solving DOPF in VSWGs Integrated Power System Using Improved Evolutionary Programming

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Abstract—Wind turbine can be divided into two categories: fixed speed wind generators (FSWGs) and variable speed wind generators (VSWGs). VSWG’s bus can be dealt with as PV-bus or PQ-bus in power flow calculation because reactive power compensation can be performed. Dynamic optimal power flow (DOPF) in VSWGs integrated power system is a typical complex multi-constrained non-convex non-linear programming problem when considering the valve-point effect of conventional generators. In this paper, an improved evolutionary programming (IEP) is proposed to solve DOPF in VSWGs integrated power system. In the methodology, the well-known evolutionary programming (EP) is used as a basic level search, which can give a good direction to the optimal global region. Then, a local search (LS) procedure is adopted as a fine tuning to determine the optimal solution. The modified IEEE 30-bus system is used to illustrate the effectiveness of the proposed method compared with those obtained from EP algorithm. In order to verify algorithm effectiveness in more complex power system, IEEE 39-bus system is used test system. It is shown that the proposed method is capable of yielding higher-quality solutions.

Index Terms—wind power generation, variable speed wind generators, dynamic optimal power flow, improved evolutionary programming

I. INTRODUCTION

Wind energy is the world’s fastest growing renewable energy source. With the increasing levels of wind generator penetration in modern power systems, one of major challenges in the present and coming years is the optimization control, such as optimal power flow including wind farms [1].

Wind turbine can be divided into two categories: fixed speed wind generators (FSWGs) and variable speed wind generators (VSWGs). FSWGs are still widely use in power system. The disadvantages of FSWGs are as follows.

When wind speed jump, huge wind force will pass through wind turbine blade, hit wind generator components including the main shaft, gearbox, engines, and so on. FSWGs mean that wind speed fluctuations are directly translated into electromechanical torque variations. This will bring in great mechanical stress and cause high fatigue damages on the components, and may result in swing oscillations between turbine and generator shaft. Also the periodical torque dips because of the tower shadow and shear effect are not damped by speed variations and result in higher flicker. Furthermore, the turbine speed cannot be adjusted with the wind speed to optimise the aerodynamic efficiency and wind energy utilization coefficient.

Compared with FSWGs, VSWGs turbine speed can be adjusted with wind speed. Mechanical stress is reduced, and gust energy can be absorbed by the means of inertia; wind energy utilization coefficient is improved, and reactive power compensation can be performed. So, VSWGs’s bus can be dealt with as PV-bus or PQ-bus in power flow calculation.

In this paper, the problems of dynamic optimal power flow (DOPF) including VSWGs are researched. The expectation model of wind generators’ active power outputs is adopted. DOPF is a typical complex multi-constrained non-convex non-linear programming problem in wind power integrated system when considering the valve-point effect of conventional generators. Both lambda-iterative and gradient technique methods in conventional approaches to the problems are calculus-based techniques and require a smooth and convex cost function and strict continuity of the search space.

In the field of global optimization, evolutionary programming (EP) was investigated and proved to be powerful in solving these problems in the last decades.
EP is a stochastic search technique with biological foundations. However, one disadvantage of EP in solving some of the multimodal optimization problems is its slow convergence to a good near-optimum\cite{2,3,4}.

In this paper, a new improved evolutionary programming (IEP) methodology is proposed for solving DOPF in VSWG's integrated power system; A simple EP\cite{5} is applied as a basic level search, which can give a good direction to the optimal global region, and a local search (LS) procedure\cite{5,7} is used as a fine tuning to determine the optimal solution at the final. IEP methodology enhances the computational accuracy and accelerates convergence rate at the later period of the searching by adopting LS operator which is invoked if fitness evaluation improves.

The modified IEEE 30-bus system and IEEE 39-bus system are used to illustrate the effectiveness of the proposed method for solving the established DOPF model in VSWG's integrated power system compared with those obtained from EP algorithm. It is shown that the proposed method is capable of yielding higher-quality solutions.

II. DOPF MODEL IN VSWG'S INTEGRATED POWER SYSTEM

Due to the random variation of the wind velocities and load demands, it is difficult to research the DOPF in the power system including wind farms. For simplifying this problem, the dividing-stage strategy is adopted in this paper. Wind power generated by wind turbines has intimate relationship with wind speed. Wind speed is converted into power through characteristic curve of a wind turbine. According to the wind velocity forecasting curves and the load forecasting curves in the planning horizon, the expectations of wind generators' power outputs and the load demands at dispatch interval can be calculated.

A. Constraints

Constraints include equality and inequality constraints. The equation constraint is the power flow formulation constraint while inequality constraints including generator power output, ramp rate and bus voltage are as in(1)-(3).

The constraints of real power generation limit and the ramp rate are taken into account as in (1).

\[
\begin{align*}
\max\left(P_{\text{min},i}^t, P_{\text{max},i}^t - D_{\text{Ri}}\Delta T\right) & \leq P_i^t \leq \min\left(P_{\text{max},i}^t, P_{\text{max},i}^t + U_{\text{Ri}}\Delta T\right), \\
i & \in N_{\text{gen}}
\end{align*}
\]

(1)

\[
Q_{\text{Gi},\text{min}} \leq Q_{\text{Gi},i}^t \leq Q_{\text{Gi},\text{max},i}, i \in N_{\text{gen}}.
\]

(2)

\[
V_{i,\text{min}} \leq V_i^t \leq V_{i,\text{max}}, i \in N.
\]

(3)

where \(P_{\text{min},i}\) and \(P_{\text{max},i}\) are the maximum and minimum limits of the power generation of unit \(i\), \(P_i^t\) is the real power output of unit \(i\) at the \(t\)-th interval, \(P_{\text{up},i}^t\) is the real power output of unit \(i\) at the \(t\)-th interval, \(U_{\text{Ri}}\) is the up-ramp limit of the \(i\)-th generator (in units of MW/time-period), and \(D_{\text{Ri}}\) is the down-ramp limit of the \(i\)-th generator (in units of MW/time-period); \(\Delta T\) is time interval, \(N_{\text{gen}}\) is the number of conventional generating units, and \(N\) is the number of system buses (excluding slack bus); \(V_i^t\) is the voltage magnitude output of bus \(i\) at the \(t\)-th interval; \(Q_{\text{Gi},i}^t\) is the reactive power output of conventional generating unit \(i\) at the \(t\)-th interval; \(\max\) is the maximum value of the variable, \(\min\) is the minimum value of the variable.

After calculating the power flow, the state variables, power loss and real power output of the slack bus generator corresponding to the current control variables are available. The real power output of the slack bus generator will be set to the limit if it violates the limit. After handling overlimit of the real power output of the slack bus generator, the system power balance constraints as in(4) must meet, otherwise adding (4) as penalty terms to the objective function to form a generalized objective function. Details of the generalized objective function used in this paper are given in section C.

\[
\Delta P = \sum_{i=1}^{N_{\text{gen}}-1} P_{i}^t + P_{i}^t + P_{\text{w},\text{av}} - P_{\text{ld},i}^t - P_{\text{ld},i}^t = 0 .
\]

(4)

where \(\Delta P\) is the unbalance of the real power at the \(t\)-th interval, \(N_{\text{gen}}-1\) represents the number of conventional generating units excluding the slack bus, \(P_{i}^t\) is the real power output of the slack bus generator after handling its overlimit at the \(t\)-th interval, \(P_{\text{ld},i}^t\) is the total power loss at the \(t\)-th interval, \(P_{\text{w},\text{av}}\) is the total load expectation at the \(t\)-th interval, \(P_{\text{w},\text{av}}\) is the expectation of wind generators' real power outputs at the \(t\)-th interval.

B. Objective Function

Due to the fact that wind generation does not consume the fuel, the utility must purchase all the energy produced by wind generating units. Consequently, the objective is to minimize the following total incremental fuel cost function \(F\) associated to \(N_{\text{gen}}\) dispatchable units for \(T\) intervals in the given time horizon, subject to the above-mentioned equality and inequality constraints.

\[
\min F = \sum_{t=1}^{T} \sum_{i=1}^{N_{\text{gen}}} F\left(P_i^t\right) .
\]

(5)

The inclusion of valve-point loading effects makes the modeling of the fuel cost function of the unit more practical. This increases the non-linearity and local optima in the solution space. Also the solution procedure can easily trap in the local optima in the vicinity of optimal value. The fuel cost function of the \(t\)-th unit \(F\left(P_i^t\right)\) with valve-point loadings are represented as follows

\[
F\left(P_i^t\right) = a_i + b_i P_i^t + c_i P_i^t^2 - e_i \sin(f_i(P_{i,\text{min}} - P_i^t)) .
\]

(6)

where \(a_i, b_i, c_i\) and \(e_i, f_i\) are cost coefficients and \(e_i, f_i\) are constants from the valve-point effect of the \(i\)-th generating unit.

C. Evaluation Function

We must define the evaluation function for evaluating the fitness of each individual in the population. In the
most of the nonlinear optimization problems, the constraints are considered by generalizing the objective function using penalty terms.

To sum up, the above problems are generalized as follows

\[
mP \frac{1}{2} \sum_{i=1}^{N_p} \sum_{k=1}^{T} \left( V_i^k - V_i^k_{\text{lim}} \right)^2 + \sum_{i=1}^{N_p} \sum_{k=1}^{T} \left( Q_i^k - Q_i^k_{\text{lim}} \right)^2 + \sum_{i=1}^{N_p} \left| P_i^k \right|^2
\]

(7)

where \( K_r, K_Q \) and \( K_D \) are variable overlimit penalty coefficients, \( V_i^k \) is the voltage magnitude of bus \( i \) at the \( k \)th interval (excluding the slack bus and PV bus); \( Q_i^k_{\text{lim}} \) is the reactive power output of generator \( i \) at the \( k \)th interval; \( V_i^k_{\text{lim}} \) and \( Q_i^k_{\text{lim}} \) denote the violated upper or lower limits.

In this paper, \( K_r, K_Q \) are set to 1, 1 respectively. Because the unbalance of the real power \( \Delta P \) is hard to meet, an adaptive penalty function to handle penalty coefficient \( K_D \) is adopted, \( K_D = \gamma k \beta a \), where \( k \) is the algorithm’s current iteration number; \( \beta \) is a relative violated value of the constraints, \( \gamma \) is a multi-assignment value, \( a \) is the power of the penalty value.

Meanwhile, several experiments have been done in order to obtain the penalty parameters. In this study, if \( \beta \leq 1 \) then \( a = 1 \), otherwise \( a = 2 \). Furthermore, if \( \beta \leq 0.001 \), then \( \gamma = 1 \), else, if \( \beta \leq 0.01 \) then \( \gamma = 10 \), else, if \( \beta \leq 0.1 \) then \( \gamma = 30 \), else, if \( \beta \leq 1 \) then \( \gamma = 100 \), otherwise \( \gamma = 300 \).

III. IEP AND IMPLEMENTS

A. Evolutionary Programming

EP is a powerful global optimization technique, has proved itself effective to handle complex optimization problems [2,3,4]. EP starts with a population of randomly generated candidate solutions and evolves towards the better solutions over a number of iterations. It uses probabilistic rules to explore the complex search space. Hence, it is more suitable to effectively handle complex optimization problems. The main stages of EP include initialization, mutation, and competition and selection. The generalized mapping procedure of the EP technique is as follows

1) Representation and initialization

For DOPF problem including VSWG, there are \( T \) dispatches by \( N_{\text{gen}} \) conventional generating units. An individual array of control variable arrays is

\[
P = \begin{pmatrix}
P_1^1 & P_1^2 & \cdots & P_1^T \\
P_2^1 & P_2^2 & \cdots & P_2^T \\
\vdots & \vdots & \ddots & \vdots \\
P_{n-1}^1 & P_{n-1}^2 & \cdots & P_{n-1}^T \\
P_n^1 & P_n^2 & \cdots & P_n^T 
\end{pmatrix}
\]

(8)

where \( P \) is individual vector, \( g \) is the number of population individuals, \( P_n^k \) is the real power output of \( n \)th generating unit at the \( k \)th interval.

For the complete \( g \) population individuals, the candidate solution of each individual is randomly initialized within the feasible range in such a way that it should satisfy the constraint given by (1).

2) Power flow and fitness calculation

Through the power flow calculation including wind farms, the state variables, power loss and real power output of the slack bus generator corresponding to the current control variables have been able to get. The real power output of the slack bus generator will be set to the limit if it violates the limit. After handling overlimit of the real power output of the slack bus generator, the system power balance constraints as in (4) must meet, otherwise adding (4) as penalty terms to the objective function to form a generalized objective function. In this paper, (7) is used as the fitness or evaluation function. This is a generalized fitness function used to evaluate the fitness of the candidate solution of each individual. Also, record the individual’s position with the global best fitness as \( g\text{Best} \), record the current position of each individual as its current \( p\text{Best} \). Set the iteration count \( k = 0 \).  

3) Creation of offspring

The value of each decision variable in the individuals of the offspring population is obtained by perturbing the corresponding variable \( p_{ij} \) in the individuals of the parents population according to

\[
p_{ij}^t[k] = \begin{cases} 
p_{ij}[k] + \sigma_{ij}[k] \cdot N_i, (0,1)[k] & \text{if } p_{ij}[k] \text{ is outside the range, it is fixed to the boundaries.} \\
\beta[k] \cdot \frac{F[k]}{F_{\text{max}}[k]} \cdot (p'_{ij,max} - p_{ij,min}) & \text{otherwise} \end{cases}
\]

where \( \sigma_{ij}[k] \) denotes the corresponding strategy parameter of \( p_{ij}[k] \) and \( N_i(0,1)[k] \) is a Gaussian random value generated anew at each time of mutation. If the \( p_{ij}[k] \) is outside the range, then \( \sigma_{ij}[k] \) is outside the range, then it is fixed to the boundaries.

\[
\sigma_{ij}[k] = \beta[k] \cdot \frac{F[k]}{F_{\text{max}}[k]} \cdot (p'_{ij,max} - p_{ij,min})
\]

where \( F[k] \) denotes the fitness value of the \( k \)th individual in the \( k \)th generation; \( F_{\text{max}}[k] \) and \( F_{\text{min}}[k] \) denote the maximum and minimum fitness in the \( k \)th generation.

where \( \beta \) is a scaling factor, which can be tuned during the process of search for optimum. The value of \( \beta \) used here was suggested by [3,4].

4) Selection and Competition

The q-tournament selection scheme is adopted in this paper. Each individual is assigned a score \( s_i \) according to

\[
s_i = \sum_{i=1}^{g} s_{ij}.
\]

(12)

\[
s_{ij} = \begin{cases} 
1 & \text{if } F_i < F_j \\
0 & \text{if } F_i > F_j
\end{cases}
\]

(13)

where \( F_i \) is the fitness of individual \( i \), \( F_j \) is the fitness of an opponent individual randomly selected from the whole \( 2N \) individuals, and \( q \) is called the tournament size. The \( N \) individuals with higher scores are selected to form the parent population of the next generation. Tournament size \( q \) is set to 0.9N in this paper.
B. LS Subroutine

EP is a powerful global optimization technique, has proved itself effective to handle complex optimization problems. However, the standard EP convergence rate is very slow [2,3,4]. Consequently, the IEP of blending the standard EP with the following LS is proposed.

The LS procedure is outlined below [6,7]. The initial search point is taken as $P_G^0$, $P_G^0 = [x_{G1}^0, x_{G2}^0, \ldots, x_{GD}^0]$ and the evaluation function value at $P_G^0$ is $F_G^0$, where $D$ is the number of dimension.

**Step 1)** The initial LS range is selected around $P_G^0$ as follows

$$
y_{\min} = p_{\min}^0 + (P_G^0 - p_{\min}) \times \beta .
$$

$$
y_{\max} = p_{\max}^0 - (P_G^0 - p_{\max}) \times \beta .
$$

$$
R = y_{\max} - y_{\min} = (p_{\max}^0 - p_{\min}^0)(1 - \beta ) .
$$

where $y_{\min}$ and $y_{\max}$ are the lower and upper boundaries of the local search region; $\beta$ is the local area parameter which is set to 0.4; $p_{\max}$ and $p_{\min}$ are the vectors of decision variables limits; and $R$ is the initial LS range $P_G^0$ (best search point at the beginning of LS) and $P_{opt}$ (optimum search point) are set to $P_G^0$.

**Step 2)** The $N_L$ LS points are randomly generated as follows

$$
p_n^m = R_{\text{best}}^{-1} \times R^{m-1} \times r(D,1), \quad n = 1, 2, \ldots, N_L .
$$

where $r(D,1)$ is a random number vector of length $D$, whose elements are randomly generated between -1 and 1 in this paper. If any LS point violates the limits, it is forced within the boundaries. $N_L$ is the number of LS points which is set to 5.

**Step 3)** For each LS point, the evaluation function values are calculated. Then the minimum evaluation function among all is taken as $F_{\text{gBest}}^m$ and the corresponding $P_G^0$ is taken as $P_{opt}$. The optimum values are updated as follows

- If $F_{opt} < F_{gBest}^m$, then $F_{opt} = F_{gBest}^m$ and $P_{opt} = P_{gBest}^m$.
- Otherwise $F_{opt} = F_{opt}$ and $P_{opt} = P_{opt}$

**Step 4)** The search range is reduced as

$$
R^m = R^{m-1} \times (1 - \eta) .
$$

where $\eta$ is the range reduction parameter which is set to 0.05.

**Step 5)** $m = m + 1$, if maximum iteration for LS is not reached, the iteration count is incremented by one and the above procedure is repeated from step 2, otherwise, $F_{opt}$ and $P_{opt}$ are taken as the optimum results found by the LS algorithm.

C. IEP and Computational Procedure

The overall procedure of the proposed solution methodology can be summarized as follows

1) Get the initial data;
2) Initialize randomly the initial population in the feasible range and iteration count $k=0$; Evaluate the initial population and identify the $F_{min}(0)$ and the best initial individual;
3) $k=k+1$,creation of new population by mutation, competition and selection;
4) Evaluate the fitness score for each individual. Identify the $F_{min}(k)$ and the best individual of the current iteration $k$;
5) If $F_{min}(k) < F_{min}(k-1)$
6) Solve the DOPF in VSGs integrated power system using the LS subroutine with the individual of $F_{min}(k)$ of the EP as starting point;
7) Replace $F_{min}(k)$ of the EP with the final solution obtained using the LS;
8) Repeat for generations until the terminal conditions $k_{max}=150$ being satisfied.

So, it is beneficial not only for global optimization in the early evolution but also for the computational accuracy and convergence rate in the later period of the searching.

The above strategies are clearly illustrated in Fig. 1.
IV. NUMERICAL RESULTS

To verify the effectiveness and efficiency of the adopted IEP for DOPF problems including VSWGs, The modified IEEE 30-bus system (see Fig.2) and IEEE 39-bus system (see Fig.3) are used as the test systems. The procedure has been implemented in Matlab 7.0 programming language and numerical tests are carried on a Pentium 4 2.4G computer. The wind farm including 60 wind generators with the same type, the rating power of which reaches 36MW, are connected to the system at the bus 6 for the modified IEEE 30-bus system and at the bus 22 for IEEE 39-bus system respectively. For simplifying the analysis, the load size is considered invariable in the planning horizon. The planning horizon is divided into 9 intervals for the modified IEEE 30-bus system and 12 intervals for IEEE 39-bus system respectively, and every interval is 1hr. The wind generators' outputs are shown in Tab. I for the modified IEEE 30-bus system and Tab. II for IEEE 39-bus system respectively. The modified IEEE 30-bus system data are given in [8]. The modified IEEE 30-bus system parameters of the conventional generating units are shown in Tab. III and Tab. IV [8, 9]. IEEE 39-bus system data are given in [8]. The IEEE 39-bus system parameters of the conventional generating units are shown in Tab. V and Tab. VI [8, 10].

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>THE WIND FARM DATA IN DIFFERENT PERIODS IN THE MODIFIED IEEE 30-BUS SYSTEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stage</td>
<td>1</td>
</tr>
<tr>
<td>$P_{w,a}(MW)$</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TABLE II</th>
<th>THE WIND FARM DATA IN DIFFERENT PERIODS IN THE IEEE 39-BUS SYSTEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stage</td>
<td>1</td>
</tr>
<tr>
<td>$P_{w,a}(MW)$</td>
<td>9</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>TABLE III</th>
<th>THE PARAMETERS OF CONVENTIONAL GENERATING UNITS IN THE MODIFIED IEEE 30-BUS SYSTEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generator</td>
<td>$a_i$</td>
</tr>
<tr>
<td>G1</td>
<td>0.0</td>
</tr>
<tr>
<td>G2</td>
<td>0.0</td>
</tr>
<tr>
<td>G12</td>
<td>0.0</td>
</tr>
<tr>
<td>G22</td>
<td>0.0</td>
</tr>
<tr>
<td>G23</td>
<td>0.0</td>
</tr>
<tr>
<td>G13</td>
<td>0.0</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>TABLE IV</th>
<th>THE LIMITS OF CONVENTIONAL GENERATING UNITS IN THE MODIFIED IEEE 30-BUS SYSTEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generator</td>
<td>$Q_{max}$ (MVAR)</td>
</tr>
<tr>
<td>G1</td>
<td>150</td>
</tr>
<tr>
<td>G2</td>
<td>60</td>
</tr>
<tr>
<td>G12</td>
<td>62.5</td>
</tr>
<tr>
<td>G22</td>
<td>48.7</td>
</tr>
<tr>
<td>G23</td>
<td>40</td>
</tr>
<tr>
<td>G13</td>
<td>44.7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TABLE V</th>
<th>THE PARAMETERS OF CONVENTIONAL GENERATING UNITS IN THE IEEE 39-BUS SYSTEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generator</td>
<td>$a_i$</td>
</tr>
<tr>
<td>G10</td>
<td>0.2</td>
</tr>
<tr>
<td>G11</td>
<td>0.2</td>
</tr>
<tr>
<td>G12</td>
<td>0.2</td>
</tr>
<tr>
<td>G13</td>
<td>0.2</td>
</tr>
<tr>
<td>G14</td>
<td>0.2</td>
</tr>
<tr>
<td>G15</td>
<td>0.2</td>
</tr>
<tr>
<td>G16</td>
<td>0.2</td>
</tr>
<tr>
<td>G17</td>
<td>0.2</td>
</tr>
<tr>
<td>G18</td>
<td>0.2</td>
</tr>
<tr>
<td>G19</td>
<td>0.2</td>
</tr>
</tbody>
</table>
TABLE VI
THE PARAMETERS AND LIMITS OF CONVENTIONAL GENERATING UNITS
IN THE IEEE 39-BUS SYSTEM

<table>
<thead>
<tr>
<th>Generator</th>
<th>$Q_{i,max}$ (MVar)</th>
<th>$Q_{i,min}$ (MVar)</th>
<th>$V_{i,max}$ (p.u.)</th>
<th>$V_{i,min}$ (p.u.)</th>
<th>$P_{i,max}$ (MW)</th>
<th>$P_{i,min}$ (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G_{30}$</td>
<td>9999</td>
<td>-9999</td>
<td>1.06</td>
<td>0.94</td>
<td>350</td>
<td>0</td>
</tr>
<tr>
<td>$G_{31}$</td>
<td>9999</td>
<td>-9999</td>
<td>1.06</td>
<td>0.94</td>
<td>1145.55</td>
<td>0</td>
</tr>
<tr>
<td>$G_{32}$</td>
<td>9999</td>
<td>-9999</td>
<td>1.06</td>
<td>0.94</td>
<td>750</td>
<td>0</td>
</tr>
<tr>
<td>$G_{33}$</td>
<td>9999</td>
<td>-9999</td>
<td>1.06</td>
<td>0.94</td>
<td>750</td>
<td>0</td>
</tr>
<tr>
<td>$G_{34}$</td>
<td>9999</td>
<td>-9999</td>
<td>1.06</td>
<td>0.94</td>
<td>1145.55</td>
<td>0</td>
</tr>
<tr>
<td>$G_{35}$</td>
<td>9999</td>
<td>-9999</td>
<td>1.06</td>
<td>0.94</td>
<td>350</td>
<td>0</td>
</tr>
<tr>
<td>$G_{36}$</td>
<td>9999</td>
<td>-9999</td>
<td>1.06</td>
<td>0.94</td>
<td>750</td>
<td>0</td>
</tr>
<tr>
<td>$G_{37}$</td>
<td>9999</td>
<td>-9999</td>
<td>1.06</td>
<td>0.94</td>
<td>750</td>
<td>0</td>
</tr>
<tr>
<td>$G_{38}$</td>
<td>9999</td>
<td>-9999</td>
<td>1.06</td>
<td>0.94</td>
<td>1145.55</td>
<td>0</td>
</tr>
<tr>
<td>$G_{39}$</td>
<td>9999</td>
<td>-9999</td>
<td>1.06</td>
<td>0.94</td>
<td>350</td>
<td>0</td>
</tr>
</tbody>
</table>

To demonstrate the superiority of the proposed approach for DOPF problems, simulation results have been compared with the EP method. Owing to the randomness in intelligent algorithms, two algorithms are executed 20 times when applied to the test system.

For DOPF problem including VSWGs, Tab. VII and Tab. VIII list the best control variables found by IEP and EP algorithm for the modified IEEE 30-bus system respectively. In Tab. VII, it is clearly shown that, by using IEP, the total production cost savings of 28.3677$/h is obtained compared with EP algorithm. Hence, it is justified that IEP approach gives the exact minimum dispatch solution. From Tab. XI, the best, worst and average cost values are 9080.5735$/h, 9200.4325$/h, 9132.5035$/h and 9108.9412$/h respectively with IEP and EP after 20 independent trials. From the results, the superiority of IEP strategies over EP can be noticed. The difference between the best and worst solutions are 119.859$/h with IEP. At the same time, the difference between the best and worst solutions is 141.226 $/h with EP. Moreover, the best and worst solutions obtained by IEP are very close to the average value, which proves that IEP is more robust and consistent. In conclusion, it is clearly shown that IEP is the most accurate and gives the exact minimum dispatch solution.

In order to verify algorithm effectiveness in more complex power system, IEEE 39-bus system is used test system. Tab. IX and Tab. X list the best control variables found by IEP and EP algorithm respectively. In Tab. IX, it is clearly shown that, by using IEP, the total production cost savings of 815.457$/h is obtained compared with EP algorithm. Hence, the same results are obtained. From Tab. XIII, the best, worst and average cost values are 460571.8601$/h, 461226.8524$/h, 460886.3652$/h respectively with IEP and EP after 20 independent trials. The difference between the best and worst solutions are 654.9923$/h with IEP. At the same time, the difference between the best and worst solutions is 1150.1183 $/h with EP.
### TABLE IX
**BEST SOLUTION OBTAINED USING IEP METHOD IN THE IEEE 39-BUS SYSTEM**

<table>
<thead>
<tr>
<th>Stage</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>P&lt;sub&gt;PG30&lt;/sub&gt; (MW)</td>
<td>297.845</td>
<td>306.2852</td>
<td>302.674</td>
<td>299.8669</td>
<td>335.2846</td>
<td>301.1622</td>
<td>294.8944</td>
<td>308.8122</td>
<td>316.6097</td>
<td>302.4517</td>
<td>276.8535</td>
<td></td>
</tr>
<tr>
<td>P&lt;sub&gt;PG31&lt;/sub&gt; (MW)</td>
<td>550.5877</td>
<td>600.1873</td>
<td>671.5014</td>
<td>605.8921</td>
<td>606.2954</td>
<td>538.8119</td>
<td>564.3921</td>
<td>584.1886</td>
<td>608.1932</td>
<td>607.222</td>
<td>600.5313</td>
<td></td>
</tr>
<tr>
<td>P&lt;sub&gt;PG32&lt;/sub&gt; (MW)</td>
<td>626.5221</td>
<td>640.2318</td>
<td>569.7617</td>
<td>622.8446</td>
<td>616.9007</td>
<td>563.5104</td>
<td>592.7636</td>
<td>569.9657</td>
<td>623.09</td>
<td>573.36</td>
<td>586.509</td>
<td></td>
</tr>
<tr>
<td>P&lt;sub&gt;PG33&lt;/sub&gt; (MW)</td>
<td>634.3726</td>
<td>610.493</td>
<td>620.8039</td>
<td>614.5901</td>
<td>634.593</td>
<td>653.5104</td>
<td>627.6324</td>
<td>639.7166</td>
<td>623.09</td>
<td>573.36</td>
<td>586.509</td>
<td></td>
</tr>
<tr>
<td>P&lt;sub&gt;PG34&lt;/sub&gt; (MW)</td>
<td>511.1227</td>
<td>476.2915</td>
<td>443.175</td>
<td>493.175</td>
<td>477.3373</td>
<td>510.5703</td>
<td>460.5703</td>
<td>472.3293</td>
<td>483.933</td>
<td>465.6822</td>
<td>491.51</td>
<td></td>
</tr>
<tr>
<td>P&lt;sub&gt;PG35&lt;/sub&gt; (MW)</td>
<td>511.1227</td>
<td>476.2915</td>
<td>443.175</td>
<td>493.175</td>
<td>477.3373</td>
<td>510.5703</td>
<td>460.5703</td>
<td>472.3293</td>
<td>483.933</td>
<td>465.6822</td>
<td>491.51</td>
<td></td>
</tr>
<tr>
<td>P&lt;sub&gt;PG36&lt;/sub&gt; (MW)</td>
<td>527.2084</td>
<td>544.5856</td>
<td>545.6563</td>
<td>542.6359</td>
<td>555.7967</td>
<td>540.9971</td>
<td>550.4644</td>
<td>548.0077</td>
<td>553.644</td>
<td>562.9881</td>
<td>562.9605</td>
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</tr>
<tr>
<td>P&lt;sub&gt;PG37&lt;/sub&gt; (MW)</td>
<td>849.1404</td>
<td>850.5165</td>
<td>832.8275</td>
<td>820.6171</td>
<td>850.6171</td>
<td>826.3819</td>
<td>827.0456</td>
<td>840.5518</td>
<td>829.1908</td>
<td>843.1028</td>
<td>819.0072</td>
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</tr>
<tr>
<td>P&lt;sub&gt;PG38&lt;/sub&gt; (MW)</td>
<td>1008.702</td>
<td>1001.955</td>
<td>1011.994</td>
<td>1012.711</td>
<td>1002.851</td>
<td>988.7539</td>
<td>999.6285</td>
<td>999.6381</td>
<td>1012.127</td>
<td>1013.031</td>
<td>1042.002</td>
<td>1043.645</td>
</tr>
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</table>

Total production cost: 460571.8601 $/h

### TABLE X
**BEST SOLUTION OBTAINED USING EP METHOD IN THE IEEE 39-BUS SYSTEM**

<table>
<thead>
<tr>
<th>Stage</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>P&lt;sub&gt;PG30&lt;/sub&gt; (MW)</td>
<td>284.7469</td>
<td>274.4208</td>
<td>274.6206</td>
<td>338.1247</td>
<td>333.3748</td>
<td>327.2719</td>
<td>306.0325</td>
<td>319.6207</td>
<td>322.2673</td>
<td>342.0072</td>
<td>305.8343</td>
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</tr>
<tr>
<td>P&lt;sub&gt;PG31&lt;/sub&gt; (MW)</td>
<td>594.6711</td>
<td>538.4092</td>
<td>504.6806</td>
<td>435.1558</td>
<td>475.9911</td>
<td>527.6847</td>
<td>564.3274</td>
<td>544.4797</td>
<td>607.5929</td>
<td>661.6504</td>
<td>646.2157</td>
<td></td>
</tr>
<tr>
<td>P&lt;sub&gt;PG32&lt;/sub&gt; (MW)</td>
<td>660.1812</td>
<td>689.5568</td>
<td>631.677</td>
<td>657.2323</td>
<td>622.9245</td>
<td>609.8651</td>
<td>565.3495</td>
<td>554.2467</td>
<td>531.8468</td>
<td>509.444</td>
<td>502.6156</td>
<td></td>
</tr>
<tr>
<td>P&lt;sub&gt;PG33&lt;/sub&gt; (MW)</td>
<td>633.0862</td>
<td>647.1537</td>
<td>657.152</td>
<td>695.4439</td>
<td>656.121</td>
<td>613.5017</td>
<td>634.5771</td>
<td>624.303</td>
<td>650.964</td>
<td>654.478</td>
<td>643.3003</td>
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</tr>
<tr>
<td>P&lt;sub&gt;PG34&lt;/sub&gt; (MW)</td>
<td>497.4557</td>
<td>495.9905</td>
<td>523.4377</td>
<td>506.0668</td>
<td>491.8216</td>
<td>456.7792</td>
<td>470.7826</td>
<td>449.7858</td>
<td>423.7924</td>
<td>451.8563</td>
<td>445.8726</td>
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</tr>
<tr>
<td>P&lt;sub&gt;PG35&lt;/sub&gt; (MW)</td>
<td>605.0152</td>
<td>616.4778</td>
<td>602.7038</td>
<td>653.1142</td>
<td>612.878</td>
<td>641.2923</td>
<td>642.1213</td>
<td>642.1213</td>
<td>650.9625</td>
<td>654.478</td>
<td>639.7837</td>
<td></td>
</tr>
<tr>
<td>P&lt;sub&gt;PG36&lt;/sub&gt; (MW)</td>
<td>544.6999</td>
<td>547.3016</td>
<td>570.5253</td>
<td>579.3393</td>
<td>565.1149</td>
<td>539.0327</td>
<td>576.4237</td>
<td>567.9087</td>
<td>554.984</td>
<td>554.984</td>
<td>545.898</td>
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</tr>
<tr>
<td>P&lt;sub&gt;PG37&lt;/sub&gt; (MW)</td>
<td>817.0216</td>
<td>835.4741</td>
<td>852.515</td>
<td>841.1737</td>
<td>846.6516</td>
<td>871.43</td>
<td>864.4906</td>
<td>894.4906</td>
<td>880.61</td>
<td>898.6867</td>
<td>872.7176</td>
<td></td>
</tr>
<tr>
<td>P&lt;sub&gt;PG38&lt;/sub&gt; (MW)</td>
<td>1001.559</td>
<td>1002.257</td>
<td>974.3036</td>
<td>980.9517</td>
<td>982.4731</td>
<td>966.97</td>
<td>992.012</td>
<td>981.4998</td>
<td>965.9799</td>
<td>989.3619</td>
<td>1013.062</td>
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</tr>
</tbody>
</table>

Total production cost: 461387.3171 $/h

The average execution time taken to complete the fixed number of iterations (T<sub>fix</sub>) for 20 trials are shown in Tab. XII for the modified IEEE 30-bus system and Tab. XIV for IEEE 39-bus system respectively.

For the modified IEEE 30-bus system, EP takes an average execution time of 1800.23 sec. to complete 150 iterations. EP converges faster than IEP by reason of the small sub-memeplex generation number of IEP. In comparison to EP, IEP has additional components, i.e., the LS procedure. This extra burdens increase the execution time of IEP. IEP takes 1898.34 sec. more than EP to complete 150 iterations. Nevertheless, IEP takes only 1020.33 sec. to converge into the lower solution range (9080–9098$/h), EP are not able to converge into the lower solution range.

For IEEE 39-bus system, EP takes an average execution time of 4247.25 sec. to complete 150 iterations. EP converges faster than IEP by reason of the small sub-memeplex generation number of IEP. In comparison to EP, IEP has additional components, i.e., the LS procedure. This extra burdens increase the execution time of IEP. IEP takes 4347.92 sec. more than EP to complete 150 iterations. Nevertheless, IEP takes only 2243.82 sec. to converge into the lower solution range (460571–460671$/h) , EP are not able to converge into the lower solution range.
### TABLE XIV
AVERAGE EXECUTION TIME COMPARISON IN THE IEEE 39-BUS SYSTEM

<table>
<thead>
<tr>
<th>Methods</th>
<th>Average execution time (sec.)</th>
<th>$T_e$</th>
<th>$T_{low}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>EP</td>
<td>4247.25</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>IEP</td>
<td>4347.92</td>
<td>2243.82</td>
<td></td>
</tr>
</tbody>
</table>

### V. CONCLUSION

Considering the valve-point effect and ramp rate limits of conventional generators including VSWGs, DOPF model, which takes the all conventional units cost minimum as the objective function and takes the whole time and the inherent relations of different stages into account in wind power integrated system, is established. The PV-bus model of VSWGs bus is adopted in power flow calculation in this paper. A novel IEP is proposed for solving the established DOPF model and the detailed methods of the algorithm are given. The modified IEEE 30-bus system is used to illustrate the effectiveness of the proposed method compared with those obtained from EP algorithm. In order to verify algorithm effectiveness in more complex power system, IEEE 39-bus system is used test system. It is shown that the proposed method is capable of yielding higher-quality solutions.

### ACKNOWLEDGMENTS

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### REFERENCES


**Gonggui Chen** was born in Hubei, China in 1964. He received his B.S. degree in physics from Huazhong Normal University, and M. Eng. degree in computer technology from Huazhong University of Science and Technology (HUST), in 1987 and 2004 respectively. He is at present a professor with the Dept. of electrical engineering, Hubei University for Nationalities, and currently pursuing the Ph.D. degree in electrical engineering in HUST. His research interests include power system analysis and operation, distributed generation and application of artificial intelligence.