The Control Technique of AGC under Regional Grid Security Constraint and Dispatching Principles of Openness, Impartiality and Fairness

Yao Zhang¹,* and Gang Yao²
¹Guizhou Electric Power Grid Dispatching and Control Center, Guiyang, China
²Guizhou Electric Power Grid Dispatching and Control Center, Guiyang, China
*Corresponding author

Abstract—Renewable energy generation (REG), including wind farms and solar plants, are continuously installed in power systems with a relatively high speed. Due to large portion of installation and intermittent characteristic, fully absorbing REG has become a troublesome problem when under certain regional grid security constraints and dispatching principles for grid dispatchers. Based on the strategy of auto generating control and the heuristic optimization method of differential evolution (DE), a novel AGC implemented with the algorithm of the variant of DE (orthogonal learning differential evolution (OLDE)) is designed to solve the problem. In this paper, a 39-node New-England system with renewable energy plants paralleled is adopted to verify the performance. The experimental results with power increasing and decreasing cases both display that the AGC can meet the demand.

Keywords—renewable energy generation; AGC; grid dispatching; orthogonal learning differential evolution

I. INTRODUCTION

In past few decades, as a positive consequence of reducing environmental pollution and of promoting economically sustainable development, there has been a remarkable increase of power generated by renewable energy (RE) in power systems[1]. Renewable energy resources (RER), including wind and solar energy, highly affected by the meteorological conditions, are mainly centralized in the partial districts. Consequently, some wind farms and solar plants are intensively paralleled in some specific regional grids[2][3]. However, due to the grid structure and load characteristic, the generating capability of RE plants can’t be totally released at some time. As a result, grid dispatchers need to manually control the generation of these RE plants under the safety of grid cross-section. On the other hand, due to the instantaneous fluctuation of the wind and solar energy, some plants with higher real-time generating capability are given lower dispatching instructions, while those with lower real-time generating capability are given higher dispatching instructions. In this case, the REG is not fully absorbed by grid, which results in the waste of RE.

Differential evolution (DE), proposed by Storn and Price[4], is a popular evolutionary algorithm used to solve the problem of optimization. It uses mutation, crossover and selection operators at each generation to move its population toward the global optimum. In general, the performance of DE mainly depends on its trial vector generation strategy (i.e., mutation and crossover operators) and its control parameters (i.e., population size, scaling factor)[5][6]. However, when the population size is large, the iterative process is time-consuming. To solve this issue, an orthogonal learning (OL) strategy based on orthogonal experimental design is developed for DE to quickly discover more useful information that contained in the winner and the loser particles.

Automatic generation control (AGC), widely used as a strong tool to control the real-time generation of traditional thermal and hydro power plants, is also implemented in the interconnected power systems with REG integrated to help maintain the equilibrium between power generation and load[7]. From the literature survey, some control techniques specializing optimization such as genetic algorithm (GA), bacteria foraging optimization algorithm (BFOA), particle swarm optimization (PSO), competitive swarm optimization (CSO) and differential evolution optimization (DEO) have been adopted in AGC controlling loop to maintain system frequency deviations and tie-line power deviations within permissible limit in response to the continuously-changing load[8][9][10][11]. Technically, these techniques have improved the dynamic response of AGC to some extent. However, the problem of REG under some specific security constraints and dispatching principles is barely discussed.

This paper, focusing on REG control strategy under certain security constraints and dispatching principles, is arranged as follows. Section 2 sorts out the mathematical formulation of the REG problem. Section 3 presents the algorithm of differential evolution (DE). Section 4 provides the details of the proposed OLDE. Section 5 displays the implementation of OLDE into the 39-node New-England system to solve the REG problem. Section 6 draws the conclusion and future work.

II. SYSTEM MODELING

A. Measurement of Margin of Cross-section

Supposing the active power of the cross-section is \( P_{\text{mcr}} \) at time, then:

\[
P_{\text{mcr}} = P_{3,1} + P_{4,2} + P_{5,3} + P_{6,4} + P_{7,5}
\]  

(1)
Where, \( P_{tP}, P_{hP}, \) and \( P_{nP} \) represent the thermal power, hydropower and RE power respectively; \( P_{dt} \) and \( P_{lt} \) represent the total load and total grid loss included in the cross-section.

In practice, due to the fluctuation of frequency and tie-line active power, a set value of the cross-section less than the theoretical value to ensure the security of grid is defined as:

\[
\Delta P_{d,t} = P_{d,t} - P_{d,\text{cal}}
\]

(2)

Where, \( P_{d,\text{cal}} \) is the theoretical value (calculated by grid engineer), while \( h_m \) is the margin coefficient (usually set under consideration of practical operation). Then the margin of the cross-section at \( t \) time is:

\[
\Delta P_{m,t} = P_{m,t} - P_{m,\text{cal}}
\]

(3)

Assuming the load of the regional grid is \( P_{dt} \) after a super-short time period (5 minutes or 1 minute), the load change can be defined as:

\[
\Delta P_{d} = P_{d,t} - P_{d}
\]

(4)

Assuming the minimum output of the thermal power and hydropower are \( P_{t\text{min}} \) and \( P_{h\text{min}} \), the amount of power can be reduced is:

\[
\Delta P_{t,k} = P_{t,k} - P_{t\text{min}}
\]

(5)

\[
\Delta P_{h,i} = P_{h,i} - P_{h\text{min}}
\]

(6)

Since the grid loss and the generation of the RE plants can be assumed invariant during the super-short time period, then the amount of additional power which can be absorbed by the regional grid is:

\[
\Delta P_{d,\text{abs},t} = \Delta P_{t,k} + \Delta P_{h,i} - \Delta P_{d}
\]

(7)

Thus, the predicted active power value of the cross-section is:

\[
P_{d,\text{abs},t} = P_{d,t} - \Delta P_{d,\text{abs},t}
\]

(8)

Then the margin of the cross-section in the upcoming super-short time will be:

\[
\Delta P_{d,\text{abs},t+1} = P_{d,\text{abs},t+1} = P_{d,\text{abs},t} - \Delta P_{d,\text{abs},t}
\]

(9)

To ensure the security of the grid, equation (9) must satisfy that:

\[
\Delta P_{d,\text{abs},t} = \Delta P_{t,k} + \Delta P_{h,i} \geq 0
\]

(10)

### B. Objective Function

\[
\min F(\mathbf{x}) = \sum_{i} w_{i} F(P_{i})
\]

subject to:

\[
\begin{align*}
\mathbf{A} \mathbf{x} & \leq \mathbf{b} \\
\mathbf{c}^{T} \mathbf{x} & \leq d
\end{align*}
\]

(11)

Where, \( F(P_{i}) \) is the total waste of RE plants paralleled within the cross-section. \( N \) is the number of the RE plants paralleled within the cross section; \( P_{i} \) is the active power instruction to the \( i \)-th RE plant; \( F(P_{i}) \) is the wasted electricity of the \( i \)-th RE plant; \( w_{i} \) is the coefficient designed to the \( i \)-th RE plant; \( m \) and \( n \) are the number of equality constraints and inequality constraints respectively; \( g_{j}(\mathbf{x}) \) is the \( k \)-th equality constraint; \( h_{k}(\mathbf{x}) \) is the \( k \)-th equality constraint.

Technically, the wasted generation of the \( i \)-th RE plant can be defined as:

\[
\Delta P_{i} = P_{i} - P_{i,\text{pre}}
\]

(12)

Where, \( P_{i,\text{pre}} \) is the predicted generation of the \( i \)-th RE plant at time \( t \).

### C. Equality and Inequality Constraint

1. The constraint of the range of the instruction \( P_{i}\text{max} \)

\[
\delta P_{i} \leq P_{i} \leq P_{i}\text{max}
\]

(13)

2. The rate of active power regulation constraint

\[
-\sigma \Delta t \leq P_{i} \leq \sigma \Delta t
\]

(14)

In equation (13), \( P_{i} \) is the operation volume of the \( i \)-th RE plant; \( d \) is the lowest power ratio designed as 0.2.

In equation (14), \( \sigma \) is the rate of active power regulation of \( i \)-th RE plant; \( P_{i}\text{max} \) is the output active power of \( i \)-th plant now; \( \sigma \) is the largest amount of regulation of \( i \)-th RE plant; \( \Delta t \) is regulation time.

From equation (13) and (14), the regulation range of active power generated from \( i \)-th RE plant is restrained as:

\[
\max [\delta P_{i} - \sigma \Delta t, \sigma \Delta t] \leq P_{i} \leq \min [P_{i}\text{max}, \delta P_{i} + \sigma \Delta t]
\]

(15)

The additional RE power absorbed by the cross-section is restrained as:
\[
\sum_{i=1}^{N} S_i (P_{i_{\text{res}}}^m - P_{i_{\text{res}}}^0) \leq \Delta P_{\text{req},i}
\]  

(16)

Where, \( S_i \) is the sensitivity coefficient of \( i \)-th RE plant with regard to the cross-section; \( \Delta P_{\text{req},i} \) is the margin of the cross-section as defined in equation (9).

D. The Measurement of the Coefficient

Considering the marketization of electricity trade and operation quality of RE plants, the author in this paper proposes the coefficient \( w_i \), defined as:

\[
w_i = \lambda_i / \gamma_i
\]

(17)

In which, \( \gamma_i \) is the ratio of the fulfillment of electricity quantity, defined as:

\[
\gamma_i = Q_i^r / Q_i^x
\]

(18)

Where, \( Q_i^r \) and \( Q_i^x \) stands for the fulfilled amount of electricity and the total scheduled amount of electricity to be completed in one month of the \( i \)-th RE plant respectively.

In addition, \( \lambda_i \) is the assessment index composed of the following parameters:

\[
\lambda_i = \mu_i x_{\text{est}}^r + 2 \mu_i x_{\text{est}}^r + \mu_i x_{\text{est}}^r + \mu_i x_{\text{est}}^r + \mu_i x_{\text{est}}^r + \mu_i x_{\text{est}}^r
\]

(19)

In which, \( x_{\text{est}}^r \), \( x_{\text{est}}^l \), and \( x_{\text{est}}^l \) are the commissioning rate, response rate, correction rate of \( i \)-th RE plant respectively; \( x_{\text{est}}^r \) and \( x_{\text{est}}^l \) are prediction accuracy rate of yesterday and of today of \( i \)-th RE plant respectively; \( x_{\text{est}}^l \) is data correction rate of \( i \)-th RE plant. In this paper, the above coefficients reflecting the plant operation are commonly set as:

\[
\mu_i = \mu_i = \mu_i = \mu_i = \mu_i = 1/6
\]

(20)

III. DIFFERENTIAL EVOLUTION (DE)

DE, based on population information, is a method that optimizes a problem by iteratively trying to improve a candidate solution (target individual) in terms of a given measure of quality. In DE, the \( i \)-th individual (solution) in \( g \)-th iteration is described as \( x_i = [x_i^1, x_i^2, \ldots, x_i^p] \), where \( i = 1,2,\ldots,p \) and \( g = 1,2,\ldots, g_{\text{max}} \).

The variation process is:

\[
x'_i = x_i^j + F \cdot (x_{\text{best}}^j - x_i^j) + F \cdot (x_i^j - x_i^j)
\]

(21)

Where \( x'_i = [v'_i, v'_i, \ldots, v'_i] \) is the variation vector derived from \( x_i = [x_i^1, x_i^2, \ldots, x_i^p] \); \( x_{\text{best}}^j \) is the best individual in \( g \)-th iteration; \( r_1, r_2, r_3, \ldots, r_5 \) are integers not equal to \( i \) and different to each other; \( F \) is the zooming coefficient controlling the zooming extent of the difference vector.

The intersection process is:

\[
u'_i = \begin{cases} 
  v'_i, & \text{if rand}(0,1) < CR \text{ or } (d = d_{\text{rand}}) \\
  x'_i, & \text{otherwise}
\end{cases}
\]

(22)

Where \( u'_i = [u'_i, u'_i, \ldots, u'_i] \) is experimental vector derived from the vector \( v'_i = [v'_i, v'_i, \ldots, v'_i] \); \( CR \epsilon [0,1] \) is crossover probability; \( \text{rand}(0,1) \) is uniformly distributed number between 0 and 1; \( d_{\text{rand}} \) is a randomly integer between 1 and \( D \).

The selection process is:

\[
x_i = \begin{cases} 
  x'_i, & \text{if } \text{fitness}(u'_i) \leq \text{fitness}(x_i) \\
  x_i, & \text{otherwise}
\end{cases}
\]

(23)

In which, \( \text{fitness}(\cdot) \) is the target function.

The main procedure of DE is shown below:

| Algorithm 1: The main procedure of DE |
|---------------------------------------|
| 1) Initialize the population           |
| 2) Evaluate the fitness of individual in initialized population |
| 3) Initialize iteration times \( g = 1 \) |
| 4) while not satisfying the ending-criteria do |
| 5) Select the best individual \( x_{\text{best}}^j \) according to the fitness value |
| 6) for \( i = 1 \) to \( p \) do |
| 7) Randomly select \( r_1, r_2, r_3, r_4, r_5 \) |
| 8) Generate the variation vector \( v'_i \) from equation (21) |
| 9) Randomly generate integer \( d_{\text{rand}} \) from \([1, D] \) |
| 10) for \( j = 1 \) to \( D \) do |
| 11) if \( \text{rand}(0,1) < CR \) or \( d = d_{\text{rand}} \) then |
| 12) \( u'_i = v'_i \) |
| 13) else |
| 14) \( u'_i = x_i \) |
| 15) end if |
| 16) end for |
for $i = 1$ to $p$ do

Evaluate the fitness of experimental individual $u_i^g$

if fitness($u_i^g$) $\leq$ fitness($u_i^e$) then

Replace $u_i^e$ with $u_i^g$

end if

end for

$g = g + 1$

end while

IV. ORTHOGONAL LEARNING DIFFERENTIAL EVOLUTION ALGORITHM (OLDE)

Against the exhaustive and time-consuming weakness of DE, the orthogonal experimental design (OED) can be used to sample a small but representative set of combinations to help find the best combination.

Take for example of the minimization of a three-dimensional function $f(x,y,z)=2x^2+3y^2+4z^2$, where $x=[x_1,x_2,x_3]=[1,3,6]$ and $y=[y_1,y_2,y_3]=[2,4,5]$ are solutions. The task is to find a combination solution from these two to make the function value minimized.

A. Orthogonal Array (OA)

OA is a fractional factorial array used to arrange experiment. The corresponding OA for the example above is:

$$L_3(2^3) = [\begin{array}{ccc}
1 & 1 & 1 \\
1 & 2 & 2 \\
2 & 1 & 2 \\
2 & 2 & 1
\end{array}]$$

The OA $L_3(2^3)$ contains 3 factors, in which, each factor has two levels (i.e. 1, 2). For the first combination (the first row), the level of the three factors are 1, which denotes the solution of $x=[1,3,6]$ and $y=[2,4,5]$ are solutions. The all 8 combinations are depicted in Fig. 1. It can be seen that although there are 8 possible combinations, only four representative ones uniformly scattering in the cube are selected by the OA $L_3(2^3)$.

TABLE I. THE EXPERIMENT RESULTS BY OL AND FA

| experiment | $x$ (level) | $y$ (level) | $z$ (level) | Fun. Value (fr) |
|------------|-------------|-------------|-------------|----------------|
| C1         | 1 (1)       | 3 (1)       | 6 (1)       | $f_1 = 173$    |
| C2         | 1 (1)       | 4 (2)       | 5 (2)       | $f_2 = 150$    |
| C3         | 2 (2)       | 3 (1)       | 5 (2)       | $f_3 = 143$    |
| C4         | 2 (2)       | 4 (2)       | 6 (1)       | $f_4 = 208$    |

level | Factor analysis

L1: $f_1 + f_2 = 323$  
$f_1 + f_3 = 316$  
$f_1 + f_4 = 381$

L2: $f_3 + f_4 = 351$  
$f_2 + f_4 = 358$  
$f_2 + f_3 = 293$

Best Level | $x$ (1) | $y$ (1) | $z$ (2) | $f_{min} = 129$

Result | 1 | 3 | 5

However, it is obvious to find that the C3 combination is not the most suitable one to make the function value minimized. Thus, we need the factor analysis to help find the most suitable combination.

B. Factor Analysis (FA)

FA, used to quickly evaluate the effect of each level in each factor, can be calculated as follows:

$$W_{r,s} = \sum_{r \in \Delta} f_i \cdot F_{r,s}$$

Where $f_i (r = 1,2,L,R)$ denotes the experimental result of $r_{th}$ combination, which is the function value in our example; $W_{r,s}$ denotes the effect of $m_{th} (m = 1,2,L,M)$ level on $k_{th}$ factor ($k = 1,2,L,K$). If the level of $k_{th}$ factor in $r_{th}$ combination is $m$, then $F_{r,k,m} = 1$; otherwise, $F_{r,k,m} = 0$.

C. Implementation of OL into DE

The OL strategy is expressed as below:

$$u_i^e = \xi \otimes x_i^e$$
Where \( x^g_i \) is the objective individual; \( u \) is the assisting phasor derived from:

\[
x = x^g + \text{rand}(0,1) \cdot (x^c - x^g)
\]

(27)

In which, \( r \in [1, ps] \) is a random individual different from \( i \); \( x^c \) is the average location of all the personalities in current population.

The candidate individual \( y^i \) derived from OL operation is described in Algorithm 2.

**Algorithm 2:** The main procedure of OL operation

1) For the objective personality \( x^g_i \)
2) Generate the assisting vector \( a \) by using equation (26)
3) Construct the corresponding OA (2)
4) Calculate the \( R \) experimental solutions \( C_r \) from the orthogonal table
5) Evaluate every function value of \( C \), \( \text{fitness}(C) \), and record the most suitable experimental result \( C \)
6) Calculate a predicted solution \( C \) by using FA, and evaluate the function value \( \text{fitness}(C) \)
7) Compare \( \text{fitness}(C) \) and \( \text{fitness}(C) \), the better solution will be candidate personality \( g \)

**D. Orthogonal Learning Differential Evolution (OLDE)**

Adding the orthogonal learning operation in each generation, the algorithm of OLDE is:

**Algorithm 3:** The main procedure of OLDE

1) Initialize the population
2) Evaluate the fitness of individual in initialized population
3) Initialize iteration times \( g = 1 \)
4) while not satisfying the ending criteria do
5) Select the best individual \( x^g_{\text{best}} \) according to the fitness value
6) Randomly select \( k \) from \([1, 2, \ldots, ps]\)
7) for \( i = 1 \) to \( ps \) do
8) if \( \text{rand}(0,1) < CR \) or \( d = d_{\text{rand}} \) then
9) \( \text{Generate } u^g_i \) by OL operation from the Algorithm 2
10) end if
11) end for
12) for \( i = 1 \) to \( D \) do
13) \( \text{if rand}(0,1) < CR \) or \( d = d_{\text{rand}} \) then
14) \( v^i = v^i \)
15) else
16) \( u^* \)
17) end if
18) \( \text{end for} \)
19) \( \text{if fitness}(u^i) \leq \text{fitness}(x^i) \) then
20) Generate \( u^i \) by OL operation from the Algorithm 2
21) end if
22) end for
23) for \( i = 1 \) to \( ps \) do
24) \( \text{Evaluate the fitness of experimental individual } u^i \)
25) \( \text{if fitness}(u^i) \leq \text{fitness}(x^i) \) then
26) \( \text{Replace } x^i \text{ with } u^i \)
27) end if
28) end for
29) \( g = g + 1 \)
30) end while

E. Constraints Transforming

From equation (11), the model with least waste of wind (photovoltaic) resource under OIF is a typical minimization problem with several constraints. With regard to the boundary constraint shown in equation (15), the complementary function is adopted to help make sure each individual can satisfy the constraint in advance. The complementary function is expressed below:

\[
x^d_{\text{new}} = \begin{cases} \text{LB}_i + \text{mod}((\text{UB}_i - \text{LB}_i), (\text{UB}_i - \text{LB}_i)) \\ \text{UB}_i - \text{mod}((\text{LB}_i - \text{UB}_i), (\text{UB}_i - \text{LB}_i)) \end{cases}
\]

(28)

Where \( \text{LB}_i \) and \( \text{UB}_i \) are the lower limit and upper limit of the variable in \( d \)-dimension respectively.

On the other hand, by adopting the punishment function, the problem of minimization with inequality constraints shown in equation (16) can be shifted with no constraints. The process is:

\[
delta = \sum_{i=1}^{N} \sum_{j=1}^{D} \Delta S_{ij} \left( P_{ij}^{\text{inj}} - P_{ij}^{\text{outj}} \right) - \Delta P_{\text{sum}}
\]

(29)

\[
\text{violation} = \max \{0, \delta\}
\]

(30)

\[
\min E(Q) = \sum_{i=1}^{N} \sum_{j=1}^{D} \left( P_{ij}^{\text{inj}} - P_{ij}^{\text{outj}} \right)^2 + \zeta \cdot \text{violation}
\]

(31)
V. THE SIMULATION RESULTS

In this part, the 39-node New-England system (shown below) is employed to validate the algorithm introduced.

![The 39-node New-England system](image)

**FIGURE II. THE 39-NODE NEW-ENGLAND SYSTEM**

In this system, the set value of the cross-section is 450MW. Meanwhile, 4 wind power farms and 2 photovoltaic power plants are paralleled within the cross-section.

**TABLE II. THE RELATED PARAMETERS OF RE PLANTS**

| RE plants | Installed capacity (MW) | Operation volume (MW) | Response rate (MW/min) | Sensitivity coefficient |
|-----------|-------------------------|-----------------------|------------------------|------------------------|
| W1        | 99                      | 92                    | 9.9                    | 0.6043                 |
| W2        | 245                     | 214                   | 15                     | 0.5261                 |
| W3        | 49.5                    | 45                    | 4.95                   | 0.5491                 |
| W4        | 100.5                   | 80                    | 10.05                  | 0.5516                 |
| PV1       | 50                      | 42                    | 5                      | 0.5742                 |
| PV2       | 65                      | 54                    | 6.5                    | 0.6518                 |

**TABLE III. THE PARAMETERS OF AGC AND PREDICTION**

| RE plants | AGC commissioning Rate | AGC response rate | AGC accuracy rate | Prediction accuracy rate of yesterday | Prediction accuracy rate in super short time | Data correction rate | Assessment index |
|-----------|------------------------|-------------------|-------------------|----------------------------------------|-----------------------------------------------|---------------------|------------------|
| W1        | 0.52                   | 0.77              | 0.91              | 0.73                                   | 0.92                                          | 0.66                | 0.75             |
| W2        | 0.72                   | 0.82              | 0.72              | 0.76                                   | 0.88                                          | 0.73                | 0.77             |
| W3        | 0.39                   | 0.75              | 0.84              | 0.68                                   | 0.91                                          | 0.69                | 0.71             |
| W4        | 0.48                   | 0.85              | 0.69              | 0.69                                   | 0.87                                          | 0.58                | 0.69             |
| PV1       | 0.61                   | 0.61              | 0.77              | 0.78                                   | 0.90                                          | 0.49                | 0.69             |
| PV2       | 0.55                   | 0.68              | 0.87              | 0.69                                   | 0.92                                          | 0.62                | 0.72             |

A. Power Increasing Case

In this case, the active power of the cross-section is 402MW. The real-time active power, the predicted generating ability together with the electricity fulfillment rate of each RE plant is shown below:

**TABLE IV. THE REAL-TIME OPERATION PARAMETER**

| RE plants | Real time generation (MW) | Prediction generation (MW) | Electricity fulfillment rate |
|-----------|----------------------------|----------------------------|----------------------------|
| W1        | 56.67                      | 75.81                      | 0.85                       |
| W2        | 127.42                     | 168.62                     | 0.71                       |
| W3        | 37.98                      | 41.55                      | 1.12                       |
| W4        | 54.51                      | 70.42                      | 0.93                       |
| PV1       | 34.07                      | 37.91                      | 1.35                       |
| PV2       | 37.33                      | 48.34                      | 0.82                       |

The coefficient of limited generating capability calculated from table 3 and table 4 is shown below:

**TABLE V. THE COEFFICIENT OF LIMITED GENERATING CAPABILITY**

| RE plant | Coefficient of limited generating capability |
|----------|---------------------------------------------|
| W1       | 1.18                                        |
| W2       | 1.41                                        |
| W3       | 0.63                                        |
| W4       | 1.08                                        |
| PV1      | 0.51                                        |
| PV2      | 1.22                                        |

Since the margin of the cross-section is \( \Delta P_{\text{min}} = 48 \text{MW} \), and the prediction generating capability is larger than the actual generation, then the AGC should increase the output power of each RE plant. The controlling process of the AGC is concluded in below:

**TABLE VI. THE GENERATION ADJUSTMENT PROCESS**

| RE plant | Real-time generation | Instruction in 1st period | Adjustment | Instruction in 2nd period | Adjustment | Instruction in 3rd period | Adjustment | Limitation |
|----------|----------------------|---------------------------|------------|---------------------------|------------|---------------------------|------------|------------|
| W1       | 56.67                | 66.57                     | 9.90       | 75.81                     | 9.24       | 75.81                     | 0.00       | 0          |
| W2       | 127.42               | 142.42                    | 15.00      | 157.42                    | 15.00      | 168.62                    | 11.20      | 0          |
| W3       | 37.98                | 41.55                     | 3.57       | 41.55                     | 0          | 37.02                     | -4.53      | 4.53       |
| W4       | 54.51                | 68.56                     | 10.05      | 70.42                     | 5.86       | 70.42                     | 0          | 0          |
| PV1      | 34.07                | 37.91                     | 3.84       | 37.91                     | 0          | 32.91                     | -5.00      | 5.00       |
| PV2      | 37.33                | 43.83                     | 6.50       | 48.34                     | 4.51       | 48.34                     | 0          | 0          |
| Cross-section Margin | 48                  | 20.92                     | -27.08     | 1.27                      | -19.65     | 0                         | -1.27      | -          |
However, due to the prediction generating capability and response rate, W3 and PV1 reach their current maximum generating capability while the other four increase their output in accord to response rate in first (the first minute) period. At the start of the second period, since the margin of cross-section is 20.92MW, the output of RE plants should continually increase. However, since W3 and PV1 have already reached their current maximum generating capability, then these two RES plants remain the same output while the other four still increase in accord to their prediction generating capability and response rate in the second period. At the end of the second period, except for W2, all of the RE plants have reached their maximum generating capability as predicted, while with the margin of the cross-section remained 1.27MW. Nevertheless, since the coefficient of limited generating capability of each RE plant is different, the AGC should not simply instruct the one, having not reached its maximum, to increase its output. In fact, as shown in table 6, W3 and PV1, both with coefficient of limited generating capability less than 1, decrease their output by 4.53 MW and 5.00MW respectively, while W2 increase larger than 1.27MW at the end of third period.

### B. Power Decreasing Case

In this case, the active power of the cross-section is 480MW. The real-time active power, the predicted generating ability together with the electricity fulfillment rate of each RE plant is shown.

| TABLE VII. THE REAL-TIME OPERATION PARAMETER |
|-----------------------------------------------|
| RE plants | Real time generation | Prediction generation | Electricity fulfillment rate |
|-----------|----------------------|-----------------------|-----------------------------|
| W1        | 82.38                | 90.4                  | 1.2                         |
| W2        | 187.64               | 200.91                | 1.1                         |
| W3        | 42.36                | 39                    | 0.95                        |
| W4        | 72.89                | 67                    | 1.28                        |
| PV1       | 40.37                | 40                    | 0.84                        |
| PV2       | 49.81                | 45                    | 0.92                        |

The coefficient of limited generating capability calculated from table 3 and table 7 is shown below:

| TABLE VIII. THE COEFFICIENT OF LIMITED GENERATING CAPABILITY |
|-------------------------------------------------------------|
| RE plant | Coefficient of limited generating capability |
|-----------|---------------------------------------------|
| W1        | 0.63                                        |
| W2        | 0.70                                        |
| W3        | 1.05                                        |
| W4        | 0.54                                        |
| PV1       | 1.19                                        |
| PV2       | 1.09                                        |

Since the margin of the cross-section is \( \Delta P_{20t} = -30 \)MW, the AGC should decrease the output power of each RE plant. The controlling process of the AGC is concluded in below table:

| TABLE IX. THE GENERATION ADJUSTMENT PROCESS |
|---------------------------------------------|
| RE plants | Real-time generation | Instruction in 1st period | Adjustment | Instruction in 2nd period | Adjustment | limitation |
|-----------|----------------------|----------------------------|------------|---------------------------|------------|-----------|
| W1        | 82.38                | 72.48                      | -9.90      | 62.58                     | -9.90      | -27.82    |
| W2        | 187.64               | 172.64                     | -15.00     | 184.30                    | 11.66      | -16.61    |
| W3        | 42.36                | 37.41                      | -4.95      | 39.00                     | 1.59       | 0         |
| W4        | 72.89                | 62.84                      | -10.05     | 52.79                     | -10.05     | -14.21    |
| PV1       | 40.37                | 37.41                      | -5.00      | 40.00                     | 4.63       | 0         |
| PV2       | 49.81                | 43.31                      | -6.50      | 45.00                     | 1.69       | 0         |

Cross-section margin -30 -1.75 -28.25 0 -1.75 -

In first period, since the cross-section is seriously overloaded, the AGC directly decrease each RE plant output at the speed of their response rate. At the start of second period, since the margin of cross-section is -1.75MW, only W1 and W4 continually decrease their output, while the others start to increase. Finally, the RE plants with coefficient of limited generating capability larger than 1 are not limited, while others are limited to different extent.

**VI. CONCLUSIONS AND FUTURE WORK**

In this paper, the algorithm of OLED applied to AGC is successfully applied to solve the problem of REG. The experimental results with regard to the dispatching order to each RE plant in each period shows the newly designed AGC can not only realize the function of automatically giving dispatching orders to guarantee the safety of grid cross-section, but also fully absorbing RE resources under the dispatching principles of OIF. In future work, AGC with function of both frequency and tie-line power control and certain operation and market mechanism constraints applied to the interconnected power systems will be investigated.

**ACKNOWLEDGMENT**

This work is supported by Science and technology project named "research and application of regional AGC control technology based on market mechanism and dispatching principles of openness, impartiality and fairness"with Grant No. 066500KK52170037 from China Southern Power Grid co.,LTD..

**REFERENCES**

[1] Junxia Liu, “China’s renewable energy law and policy: A critical review”, Renewable and Sustainable Energy Reviews, pp.212-219; Oct. 2018.

[2] E. Mortaz, J. Valenzuela, “Evaluating the impact of renewable generation on transmission expansion planning”, Electric Power Systems Research, pp.35-44; Dec. 2018.

[3] E. Mortaz, J. Valenzuela, “Evaluating the impact of renewable generation on transmission expansion planning”, Electric Power Systems Research, pp.35-44; Dec. 2018.
[4] R. Storn, K. Price, “Differential evolution – a simple and efficient heuristic for global optimization over continuous spaces”, Journal of Global Optimization, 1997; 11:341-359.

[5] S. Das, P. N. Suganthan, “Differential evolution: A Survey of the State-of-the-Art”, IEEE Trans. Evol. Comput., vol. 15, no. 1, pp. 4-31, Feb. 2011.

[6] R. Mallipeddi, P. N. Suganthan, Q. K. Pan, M. F. Tasgetiren, “Differential evolution algorithm with ensemble of parameters and mutation strategies”, Applied Soft Computing, pp. 1679-1696; May. 2010.

[7] Mewara, G. Parmar, “Comparison of DE Optimized PID Controllers for AGC of Interconnected Power System”, 2017 International Conference on Computer, Communications and Electronics (Comptelix), pp.178-182.

[8] Yong Wang, Zixing Cai, Qingfu Zhang, “Differential Evolution with Composite Trial Vector Generation Strategies and Control Parameters”, IEEE Trans. Evol. Comput., vol. 15, no. 1, pp. 55-66, Feb. 2011.

[9] P. Saraswat and G. Parmar, “A comparative study of Differential Evolution and Simulated Annealing for order Reduction of Large Scale Systems”, IEEE Conference on Communication, Control and Intelligent Systems(CCIS-2015), Nov.7-8,2015.

[10] S. Panda, “Multi-objective evolutionary algorithm for SSSC-based controller design”, Electric Power Systems Research, 2009; 79:937-44.

[11] S. R. Khuntia, S. Panda, “Simulation study for automatic generation control of a multi-area power system by ANFIS approach”, Applied Soft Computing