

# Research about the Penetrating Power Limitation of Photovoltaic Based On Power Balance

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**Abstract.** Considering the shortages of the traditional algorithms, this paper proposes a new method to calculate the penetrating limitation of PV from the view of the power balance. Artificial fish swarm algorithm (AFSA) with mutation operator and fruit fly optimization algorithm (FOA) is presented to improve the accuracy and efficiency by using unit commitment and time as decision variables, and penetrating power limitation as objective function. The simulation results show that the important factors to determine penetrating power limitation of PV are the output characteristics of PV power, the output characteristics of conventional units and the load characteristics of power generation. Numerical results prove the correctness and effectiveness of this hybrid algorithm.

## 1. Introduction

In recent years, with the development of photovoltaic (PV) in China, the scale of the PV power station is increasing [1]. The PV power has a fluctuant output power to the grid because of multiple factors. Also the analysis of the influence is complex. Therefore, there is no a unified method to solve its penetrating limitation of renewable energy. The penetrating power limitation is calculated directly by principle of optimization. The process of calculation is simple and the correctness of the result would not be affected by the operation modes of power system [2].

From the perspective of mathematical, the power generation limitation of PV is a kind of combinatorial optimization problems, including the characteristics of nonlinear, multi-objective and uncertainty [3]. At present, the methods which use to solve the problem involving the constraint programming can be approximately divided into three categories: 1) heuristic method based on the intuitive analysis; 2) optimization method based on the strict mathematical demonstration; 3) intelligent optimization algorithm originated from the natural laws and computing science [4-6]. This kind of algorithms which has advantages of a loose demanding for objective functions and constraint functions, an ability to jump out of local minima and high efficiency of calculation, is becoming a popular issue. In addition to the mature intelligent optimization algorithms, several emerging intelligent optimization algorithms are also gradually arose, which provide new ideas and means to solve the optimization problems [7].

Therefore, this paper adds mutation operator of artificial fish swarm algorithm (AFSA) with fruit fly optimization algorithm (FOA), which is proposed mutation operator and FOA into AFSA to form a hybrid algorithm. Taking the stability, economy, safety and reliability of the power system into



consideration, this paper proposes a method to determine the penetrating power limitation of PV which is based on the power balance.

## 2. Penetrating power limitation of PV based on the power balance

The PV generation systems are mainly composed of PV arrays, controllers and inverters. Among of them, the core part is PV arrays. The output power of PV arrays is expressed as below [8]:

$$P_{solar} = rA\eta \quad (1)$$

Where  $r$  is the irradiance of solar with  $W/m^2$ ,  $A = \sum_{m=1}^M A_m$  and  $\eta = \frac{\sum_{m=1}^M A_m \eta_m}{A}$  are the area and

photoelectric conversion efficiency of PV arrays respectively,  $M$  is the number of battery components for PV arrays,  $A_m$  and  $\eta_m$  are the area and photoelectric conversion efficiency of the single PV cell respectively. In a certain period, the light irradiance  $r$  is approximate to *Beta* distribution, and its probability density function is as shown in (2):

$$f(r) = \frac{\Gamma(\alpha + \beta)}{\Gamma(\alpha)\Gamma(\beta)} \left(\frac{r}{r_{\max}}\right)^{\alpha-1} \left(1 - \frac{r}{r_{\max}}\right)^{\beta-1} \quad (2)$$

Where  $r_{\max}$  is the maximum irradiance of solar with  $W/m^2$ ,  $\alpha$  and  $\beta$  are the shape parameters of *Beta* distribution respectively. From the formula (2), the probability density function of  $P_{solar}$  is as follows:

$$f(P_{solar}) = \frac{\Gamma(\alpha + \beta)}{R_{solar}\Gamma(\alpha)\Gamma(\beta)} \left(\frac{P_{solar}}{R_{solar}}\right)^{\alpha-1} \left(1 - \frac{P_{solar}}{R_{solar}}\right)^{\beta-1} \quad (3)$$

Where  $R_{solar} = r_{\max} A\eta$  is the maximum output power of solar arrays.

Ignoring the loss of active power changing by PV generation, the power balance equation including the generator, load and loss of active power is computed by:

$$P_{solar}(t) + \sum_{i=1}^N P_{uti} \geq \sum_{i=1}^M P_l(t) + \Delta P(t) \quad (4)$$

Where  $P_{solar}(t)$  is the output power of PV at the time of  $t$ ,  $\sum_{i=1}^N P_{uti}$  is the total active power of the

conventional generator at the time of  $t$ ,  $\sum_{i=1}^M P_l(t)$  is the supply load of the power system at the time of  $t$ ,

and  $\Delta P(t)$  is the active power loss of system at the time of  $t$ .

The loss of lines is a nonlinear function which is shown in formula (4), and its calculation results can be obtained by flow equations. Therefore, the model which is removed the loss of lines can be simplified as:

$$P_{solar}(t) + \sum_{i=1}^N P_{uti} \geq \sum_{i=1}^M P_l(t) \quad (5)$$

At the moment of  $t$ , there is a relationship between the output power of PV generation and its installed capacity:

$$P_{solar}(t) = P_{solarC} \eta_{solar}(t) \tag{6}$$

In which  $P_{solarC}$  is the installed capacity of the PV generation,  $\eta_{solar}(t)$  is the per unit value of output power of PV generation which is various with  $t$ . In order to simplify the model, it is taken into account the power loads which are equal to the sum of the PV generations and conventional power supplies.

$$P_{solarC} = \frac{\sum_{i=1}^M P_i(t) - \sum_{i=1}^N P_{uti}}{\eta_{solar}(t)} \tag{7}$$

With the different combinations of generator, the lower limitations of  $\min(\sum_{i=1}^N P_{uti})$  are diverse.

Assuming that the number of units in the grid is  $N$ ,  $P_{ui}$  is the active power for the unit of  $i$ , which the output ranges from lower limit  $P_{ui\min}$  to upper limit  $P_{ui\max}$ . Set  $N$  dimensional vectors  $U = [u_1, \dots, u_i, \dots, u_N]$  as state vectors of generators, which  $u_i = 0$  means halt mode and  $u_i = 1$  means starting up mode.

In conclusion, the penetration limitation of PV at the time of  $t$  is expressed as follows:

$$P_{solarP}(t) = \max_{U_i \in \Omega} \left( \frac{\sum_{i=1}^M P_i(t) - U_i P_{\min}^T}{\eta_{solar}(t) P_{I\max}} \times 100\% \right) \tag{8}$$

Where  $P_{\min} = [P_{1\min}, \dots, P_{i\min}, \dots, P_{N\min}]$  is the derating vector of unit generation,  $\Omega$  is the interval of the unit state vectors, and  $P_{I\max}$  is the largest load of power system.

In order to meet the requirements of reliability and economy of the power system, the variables in formula (8) shall satisfy the following constraint conditions [9].

1) Constraints of power balance:

$$U_t P_{\min}^T \leq \sum_{i=1}^M P_i(t) \leq U_t P_{\max}^T \tag{9}$$

2) Constraints of units output:

There are maximum and minimum limitations when the units are designed and operated, which can be expressed as:

$$P_{i\min} \leq P_{ui}(t) \leq P_{i\max} \tag{10}$$

Wherein  $P_{i\min}$  and  $P_{i\max}$  are the minimum and maximum limitations of the unit  $i$ .

3) Constraints of ramping up and down of the units:

When the generations are increasing output power, the speed is smaller than its maximum output; moreover, the generations are decreasing output power, the speed is less than its maximum output.

$$-r_{di} \times 1h < [P_{ui}(t-1) - P_{ui}(t)] < r_{ri} \times 1h \quad (11)$$

Where  $r_{di}$  and  $r_{ri}$  are the maximum ramping down and up output of unit  $i$ .

In order to simplify the constraint conditions, the formula (10) and (11) could be simplified further. Set  $P_{idown} = \max[P_{imin}, P_i(t) - r_{di}]$  and  $P_{iup} = \min[P_{imax}, P_i(t) + r_{ri}]$ , thus,  $P_i$  can be determined by:

$$P_{idown} \leq P_i \leq P_{iup} \quad (12)$$

4) Constraints of spinning reserve:

$$U_i P_{max}^T \geq \sum_{i=1}^M P_i(t) + R_t \quad (13)$$

Where  $R_t$  is the spinning reserve in the power system.

5) Constraints of unit state vectors:

$$u_i \in \{0, 1\} \quad (14)$$

### 3. Improvement of AFSA

#### 3.1. Fundamentals of AFSA and its improvement

Inspired by swarm intelligence, AFSA is an artificial intelligent algorithm based on the simulation of collective behavior of swarms of fish. It simulates the behavior of a single artificial fish (AF), and then constructs a swarm of AF [10]. Each AF will search its own local optimum and pass on information in its self-organized system and finally achieve the global optimum. The AFSA has the ability to grasp the search direction and avoid falling into the local optimal. But when some fishes move in aimless random or gather around the local optimal, the speed of convergence will be slow down greatly, and the searching accuracy is greatly reduced. In order to overcome this drawback, the mutation operator similar as genetic algorithm is introduced in this paper. If the state of AF is not improved during the iterations and the AF has been entered into a state of partial mining, it is needed to mutate.

The specific steps are as follows: 1) randomly selecting one of the variables in the position to add one, and choosing the non-null to subtract one. 2) If the state is better than that of the current state, then updates the state of position, otherwise, turn to step (1) until meeting the initial number of the mutating. By adding the mutation mechanism into the AFSA, it is achieved the aim of altering of the AF. Through adjusting the swarms, the rate of convergence and global searching ability of AFSA are improved. The choice of mutation probability will have a great influence on the performance of the algorithm, which is positive correlation to the time-consuming. According to the experimental experience, the probability of mutation which is adopted by  $1/(30D) \sim 1/(10D)$  ( $D$  is the dimension.) can obtain a good effect. Usually, the mutating probability of an AF is assumed as 0.03~0.1.

#### 3.2. Designing of the hybrid ASFA

Fruit fly optimization algorithm (FOA) is a new swarm intelligence method, which was proposed by Pan, and it belongs to a kind of interactive evolutionary computation [11]. The FOA is a new method for finding global optimization based on the food finding behavior of the fruit fly. The fruit fly is

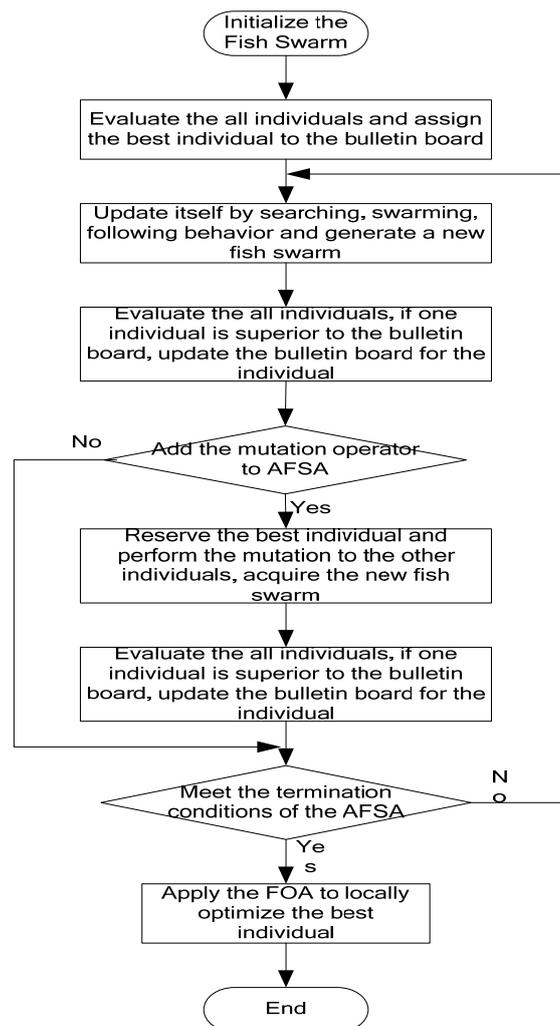
superior to other species in vision and osphresis. The food finding process of fruit fly is as follows: firstly, it smells the food source by osphresis organ, and flies towards that location; then, after it gets close to the food location, the sensitive vision is also used for finding food and other fruit flies' flocking location, and it flies towards that direction.

Considering the above ideal, the AFSA with mutation operator can quickly find the satisfying domain of optimal solution and the FOA has the advantage of strong local searching ability. Firstly, the AFSA with mutation operator determines the domain of optimal solution; then, the FOA employs local optimization of the AF in the satisfying domain; finally, the best precise extremum is obtained. The basic flow chart of AFSA with the mutation operator and FOA is shown in Figure 1.

**4. Analysis of examples**

The simulation is based on the 10-machines system combining with the output characteristics of PV in the power system [12]. Figure 2 and Table 1 show the power loads and parameters of units in a normal day, respectively. According to the actual situation of power grid, the spinning reserve capacity accounts for 8% proportion of the maximum power loads and the maximum rate of changing of the PV output power is 20%. Table 2 shows the parameters of the algorithms.

This paper uses the mentioned algorithms to calculate the penetrating power limitations of PV generation in a normal day. The penetrating power limitations in per hour are as shown in Table 3.



**Figure 1** Basic flow chart of AFSA with mutation operator and FOA

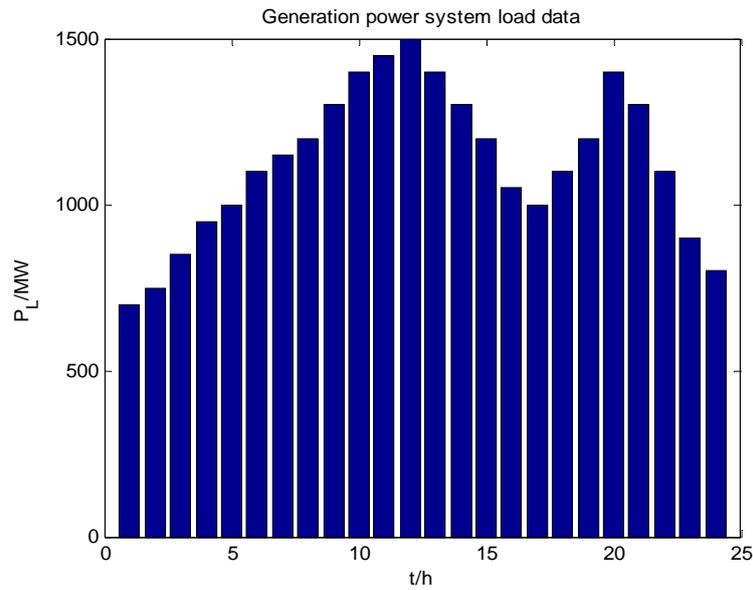


Figure 2 Generation power system load data

Table 1 Characteristics of power system generator

<i>i</i>	$P_{min}/MW$	$P_{max}/MW$	<i>i</i>	$P_{min}/MW$	$P_{max}/MW$
1	150	455	6	20	80
2	150	455	7	25	85
3	20	130	8	10	55
4	20	130	9	10	55
5	25	162	10	10	55

Table 2 Parameters of the algorithms

Parameters						
Name	<i>N</i>	$G_{max}$	<i>Step</i>	<i>Visual</i>	<i>Try_number</i>	$\delta$
Value	20	50	0.3	1.8	10	0.618
Name	$P_m$	<i>maxgen</i>	<i>sizepop</i>	<i>X axis</i>	<i>Y axis</i>	<i>FR</i>
Value	[0.03, 0.1]	100	10	[0, 1]	[0, 1]	[-10, 10]

**Table 3** Unit power status and penetrating power limitation of PV power generation. (A/B: A is the result by the AFSA; B is the result by the AFSA with mutation operator and FOA.)

t/h	i										P <sub>solarP</sub> /%
	1	2	3	4	5	6	7	8	9	10	
1	0/1	1/0	0/1	1/0	1/1	0/0	0/0	0/1	1/1	1/0	+∞/+∞
2	0/1	1/0	0/0	1/1	1/1	0/0	0/0	1/1	1/1	1/1	+∞/+∞
3	0/0	1/1	1/1	1/1	1/1	0/1	0/0	1/0	1/0	1/1	+∞/+∞
4	0/0	1/1	1/1	1/1	1/1	1/1	0/0	1/1	1/1	1/1	+∞/+∞
5	0/1	1/0	1/1	1/1	1/1	1/1	1/1	0/1	1/1	1/0	+∞/+∞
6	1/1	1/1	0/1	1/0	1/1	0/0	0/0	0/0	0/0	1/1	+∞/520
7	1/1	1/1	0/1	1/1	1/1	0/0	0/0	0/0	1/0	1/0	405/380
8	1/1	1/1	0/1	1/1	1/1	0/0	0/0	1/0	1/0	1/1	150/102
9	1/1	1/1	1/1	1/1	1/1	0/1	0/0	1/0	1/0	1/1	68/55
10	1/1	1/1	1/1	1/1	1/1	0/1	1/0	1/1	1/1	1/1	40/32
11	1/1	1/1	1/1	1/1	1/1	1/1	1/1	0/1	1/1	1/0	28/18
12	1/1	1/1	1/1	1/1	1/1	1/1	1/1	0/1	1/1	1/1	20/15
13	1/1	1/1	1/1	1/1	1/1	1/0	0/1	1/1	1/1	1/1	25/18
14	1/1	1/1	1/1	1/1	1/1	0/1	0/0	1/0	1/0	1/1	30/24
15	1/1	1/1	0/1	1/1	1/1	0/0	0/0	1/0	1/0	1/1	25/17
16	0/1	1/0	1/1	1/1	1/1	1/1	1/1	1/1	1/1	1/0	22/16
17	0/1	1/0	1/1	1/1	1/1	1/1	1/1	0/1	1/1	1/0	30/19
18	1/1	1/1	0/1	1/1	1/0	0/1	0/0	0/0	0/0	1/0	45/38
19	1/1	1/1	0/0	1/1	1/1	0/1	0/0	1/0	1/0	1/1	138/112
20	1/1	1/1	1/1	1/1	1/1	1/1	0/0	1/1	1/1	1/1	+∞/+∞
21	1/1	1/1	1/1	1/1	1/1	0/1	0/0	1/0	1/1	1/1	+∞/+∞
22	1/1	1/1	0/1	1/0	1/1	0/0	0/1	0/1	0/0	1/0	+∞/+∞
23	0/1	1/0	1/1	1/1	1/1	1/1	0/1	0/0	1/0	1/0	+∞/+∞
24	0/0	1/1	1/1	1/1	1/1	0/0	0/0	0/0	1/1	1/1	+∞/+∞

Table 3 lists the whole day penetrating power limitations with AFSA and hybrid AFSA. To ensure the safety and stability of the power system, it should be set the minimal penetrating limitation as the penetrating power limitations of PV in the whole working period, namely:

$$P_{solarP} = \min_{t_{on} \leq t \leq t_{off}} (P_{solarP}(t)) \tag{15}$$

Where  $t_{on}$  and  $t_{off}$  are the time of beginning and ending, respectively.

Table 3 shows that the penetrating power limitations of PV generations are varying with the time. At noon, the minimal penetrating power limitation of PV is 20% by the AFSA while that is 15% by the hybrid AFSA during the whole day time. According the formula (16), the penetrating power limitations of PV are setting as 20% by the AFSA and 15% by the hybrid AFSA. In an actual power system, if the simulating result of penetrating limitation is larger than the limit capacity of reality, it will have a great threaten to the stability of the grid. Therefore, the penetrating power limitation of PV generation by the hybrid AFSA is more credible than that by AFSA.

**5. Conclusion**

This paper introduces a new hybrid algorithm, AFSA optimized by mutation operator and FOA, to obtain the penetrating power limitation of PV generation which connected to grid. Firstly, penetrating power limitation which based on power balance is proposed in this paper. By setting time and unit

commitment as decision variables, objective function is defined as penetrating power limitation. Secondly, the new hybrid algorithm uses the AFSA with mutation operator to find the domain of the global convergence quickly, then, reuses the FOA to search the local optimization. The hybrid algorithm not only has the ability of global searching, but also guarantees the accuracy of the local searching. Thirdly, to ensure the safety and stability of the power system, this paper proposes to set the minimal penetrating limitation as the penetrating power limitations of PV generation in the whole working period.

## 6. References

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