Optimized Capacity Configuration of an Integrated Power System of Wind, Photovoltaic and Energy Storage Device Based on Improved Particle Swarm Optimizer

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***Abstract*—To enhance power supply reliability of wind-PV power system and improve utilization of wind power and PV, it is necessary to configure the capacity of wind turbine generators, PV modules and energy storage devices reasonably. Based on the feature of joint-operation of wind-PV generation system with energy storage device and considering dynamic variation of stored energy during the joint operation, taking technical characteristics of energy storage unit and the loss of power supply probability (LPSP) as the constraint, a joint configuration method of wind power capacity, PV and energy storage capacity, in which the original investment of integrated power system of wind, photovoltaic and energy storage device is taken as objective function, is proposed. An improved particle swarm optimizer (IPSO) is proposed. In the algorithm, the value of inertia weight was directed by the distance between the particle and the global optimal particle, crossover and mutation operations were introduced to avoid falling into local optimal solution. Under the conditions of a given case, take the lithium-ion battery into account. And simulation results show that the method has rapid convergence speed and superb global search ability.**

Keywords—Wind-PV power system, energy storage device, particle swarm optimizer, loss of power supply probability, capacity configuration.

I. INTRODUCTION

Wind power and photovoltaic power generation use Wind and solar as a source of energy. But wind power and solar power are easy to be affected by environment and climate[1]. When wind power and photovoltaic power generation large-scale access to the grid, it will have a great impact on safe and stable grid operation [2-3]. To smooth the wind output fluctuations, reducing its access to the adverse effects on the grid, a certain capacity of the energy storage system is used. How to select the capacity of energy storage system is the urgent need to solve the problem.

Currently, There is a lot of research on energy storage unit capacity optimization configuration. Mainly in three areas: 1) Stabilize large-scale wind farm power fluctuation energy storage configuration[4-5] .2)Maintain micro-grid system stable economic operation energy storage configuration[6-7]. 3) Other areas of application configuration energy storage, such as maintaining system stability, peak load shifting[8-9].

II. A TYPICAL STRUCTURE OF WIND-PV POWER SYSTEM

The typical structure of wind-PV power system is shown in Fig. 1, which consists of four parts: wind turbine, PV module, battery energy storage system and local load. In the figure, C_0 is a one-way DC-DC converter, which is used to boost the photovoltaic power generation unit and track the maximum power of the PV. C_1 is a one-way DC-AC inverter, which is used to convert DC power to alternating current. C_2 is a bidirectional DC-DC converter, which is used to control the charging and discharging process of the energy storage unit and to provide voltage support for the DC bus.The photovoltaic power generation unit and the energy storage unit are assembled to the DC common bus through the respective DC / DC converter, and then connected to the AC bus by the common DC / AC inverter, and the power supply is shared with the wind turbine. The wind storage and power generation system is connected with the power grid through the point of common coupling (PCC).

This paper only considers the independent operation mode of integrated power system of wind, photovoltaic and energy storage device.

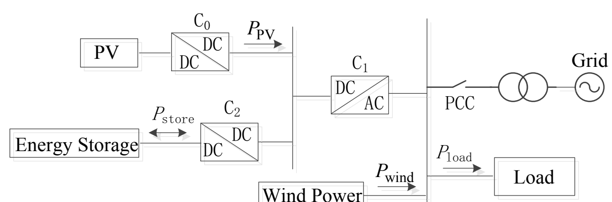

Fig. 1 Structure of wind-PV power system

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III. Optimization Model of wind-PV power system

A. Objective Function

The capacity configuration of the wind-PV power system is affected by many factors. It is a multi-objective optimization problem, but many influencing factors can be regarded as an economic problem. Therefore, this paper takes the initial investment of wind-PV power system as the objective function to solve the problem.

$$\min C_{\mathrm{sys}} = C_{\mathrm{E}} E_{\mathrm{rate}} + C_{\mathrm{PCS}} P_{\mathrm{rate}} + C_{\mathrm{PV}} P_{\mathrm{Vrate}} + C_{\mathrm{wind}} P_{\mathrm{Wrate}} \tag{1}$$

C_{sys} is the total initial investment of the system.

C_{E} is the unit cost of the energy storage unit.

E_{rate} is the storage capacity of the energy storage unit.

C_{P} is the unit power cost of the energy storage unit .

P_{rate} is the rated power of the energy storage unit.

C_{PCS} is the unit power cost of the energy storage unit energy conversion system.

C_{PV} is the unit power cost of photovoltaic unit.

P_{Vrate} is the rated power of photovoltaic unit.

C_{wind} is the unit cost of wind power generation.

P_{Wrate} is the rated power of wind power generation.

B. Constraint Condition

With wind-PV power system independent operation, in order to ensure the normal load power supply, we should first consider the real load inside the system balance. In this paper, LPSP is a constraint when solving the problem, considering the technical characteristics of energy storage devices at the same time.

LPSP represents the probability that the system power generation cannot meet the load demand for a certain period of time. In the evaluation period T, LPSP can be expressed as the ratio of the load shortage in the period to the total load demand. In the wind-PV power system, loss of power supply within the time Δt can be expressed as

$$Q_{\mathrm{LPS}}(t) = [P_{\mathrm{load}}(t) - P_{\mathrm{PV}}(t)\eta_1 - P_{\mathrm{wind}}(t)]\Delta t \tag{2}$$

In equation (2):

$P_{\mathrm{load}}(t)$ is the system load demands at time t

$P_{\mathrm{PV}}(t)$ is the average power of the PV module at time t

η_1 is the efficiency of the inverter C_1

$P_{\mathrm{wind}}(t)$ is the average power of the wind power at time t

Loss of power supply should be positive, so $Q_{\mathrm{LPS}}(t)$ can be calculated as equation (3)

$$\overline{Q_{\mathrm{LPS}}}(t) = \begin{cases} Q_{\mathrm{LPS}}(t), & Q_{\mathrm{LPS}}(t) \ge 0 \\ 0, & Q_{\mathrm{LPS}}(t) < 0 \end{cases} \tag{3}$$

δ_{LPSP} (LPSP) can be calculated as equation (4)

$$\delta_{\mathrm{LPSP}} = \sum_{t=t_0}^{t_0+n\Delta t} \overline{Q_{\mathrm{LPS}}}(t) \Big/ \sum_{t=t_0}^{t_0+n\Delta t} [P_{\mathrm{load}}(t)\Delta t] \tag{4}$$

In equation (4):

t_0 is the initial time

n is the time series

Considering the energy storage unit, formula (4) can change into

$$\delta_{\mathrm{LPSP}} = \frac{\sum_{t=t_0}^{t_0+n\Delta t} \{P_{\mathrm{load}}(t) - P_{\mathrm{wind}}(t) - [P_{\mathrm{PV}}(t) + P_{\mathrm{store}}(t)\eta_2\eta_{\mathrm{d}}]\eta_1\}\Delta t}{\sum_{t=t_0}^{t_0+n\Delta t} P_{\mathrm{load}}(t)\Delta t} \tag{5}$$

IV. Improved Particle Swarm Optimization Algorithm

A. Particle Swarm Algorithm

Particle swarm algorithm is a stochastic optimization algorithm, which is initialized as a group of random particles. Particles in the solution space according to their own and group information to determine the speed and direction of its motion, through iterative search for the optimal solution. Each particle is updated by iterating to update its own speed and position by tracking two "optimal solutions", as follows:

$$v_{id}^{(k+1)} = wv_{id}^{(k)} + c_1 r_1 (p_{id}^{(k)} - x_{id}^{(k)}) + c_2 r_2 (g_d^{(k)} - x_{id}^{(k)}) \tag{6}$$

$$x_{id}^{(k+1)} = x_{id}^{(k)} + v_{id}^{(k+1)} \tag{7}$$

In equation (6) (7):

w is the inertia weight

c_1 、 c_2 are the accelerating factor

r_1 、 r_2 are the random number ranging from 0 to1

$p_{id}^{(k)}$ is the d-dimension component of the optimal position vector of particle i at time k

$g_d^{(k)}$ is the d-dimension component of the optimal population position vector at time k

B. Improved Particle Swarm Optimization

a) Adaptive inertia weight

In the PSO algorithm, the value of w (the inertia weight) has an important effect on its convergence performance. Most methods of the value w are linearly or non-linearly decreasing as the number of iterations increases. This method does not take into account the characteristics of the particles in the iterative process.

In this paper, the difference between the particle and the optimal particle size of the population as a guide to the value of w, with the degree of the difference between the non-linear adjustment of the size of w, the value of the curve shown in Figure 2.The difference between the *i*-th particle and the global optimal solution of population at $X_i^{(k)}$ can be calculated by the following formula:

$$X_i^{(k)} = \frac{1}{x_{\max} - x_{\min}} \frac{1}{D} \sum_{d=1}^{D} | g_d^{(k)} - x_{id}^{(k)} | \tag{8}$$

$$w_i^{(k)} = w_{\text{start}} - (w_{\text{start}} - w_{\text{end}})(X_i^{(k)} - 1)^2 \tag{9}$$

In equation (8) (9):

D is the solution space dimension

$w_i^{(k)}$ is the *i*-th particle at time *k*

w_{start} 、 w_{end} are the initial and end values of *w*

$x_{\max}$ 、 $x_{\min}$ are the maximum and minimum values of the particle position variables

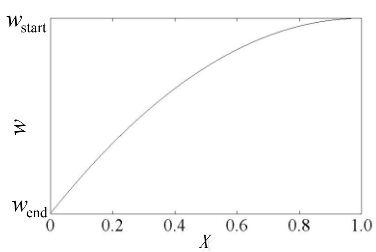

Fig. 2 Inertia weight curve

b) Cross variation

PSO algorithm in the iterative optimization of premature convergence problems, easy to fall into the local solution. In this paper, the crossover operation in the genetic algorithm is introduced into the particle swarm optimization algorithm, and the position vector of the particle is cross-mutated to improve the diversity of the population. Taking the difference X of the global optimal solution of the particle position vector and the population as the basis of the cross variation, the concrete steps are as follows:

1. Determine the threshold $X_{\min}$, the crossover rate p_{c} and the variance of the difference p_{m}.

2. Determine the size of X_i, if $X_i < X_{\min}$, the particles *i* cross-mutation, or go to step 5.

3. For each dimension of the particle i, select a random number r_{id} ranging from 0 to 1. If $r_{id} < p_m$, the d-dimensional position component of particle i is initialized. The operation method is as equation (10).

4. Cross the position vector of variant particle. If $r_{id} < p_{\text{c}}$, cross the other d-dimension of position vectors. The crossed object is the global optimal solution of the population. The operation method is shown in Fig. 3.

5. Cross mutation ends.

$$x_{id} = x_{\min} + (x_{\max} - x_{\min}) \cdot r \tag{10}$$

In equation (10) :

$x_{\min}$ is the minimum value of the particle position variable

r is the random number ranging from 0 to 1

$$\begin{array}{l} x_i = [x_1, x_2, \cdots, x_d \cdots, x_D] \\ \qquad\qquad\qquad\quad \uparrow r_{id} < p_c \\ g = [g_1, g_2, \cdots, g_d \cdots, g_D] \end{array}$$

Fig. 3 Schematic diagram of crossover operation

V. SOLUTION OF CAPACITY OPTIMAL ALLOCATION FOR WIND-PV POWER SYSTEM

A. Calculation of Power and Capacity Requirements for Energy Storage Devices

In the wind-PV power system, the target of capacity allocation is to ensure the energy balance of the system under certain load conditions and the minimum initial investment of the system.

a) Energy storage power requirements

In the evaluation period T, set ΔP as the system power imbalance at t time ,

$$\Delta P(t) = [P_{\text{load}}(t) - P_{\text{wind}}(t)] / \eta_1 - P_{\text{PV}}(t) \tag{11}$$

In equation (11), the size of ΔP is random, which is closely related to the output characteristics of the wind power generation system and the demand characteristic of the load. If $\Delta P(t) > 0$, the energy storage unit is required to discharge. If $\Delta P(t) < 0$, the energy storage unit is required to charge.

In the case of power configuration, the energy storage unit is required to supply or absorb the maximum power shortage P_1 or the maximum excess power P_2 during the period T. The rated power of energy storage unit can be calculated as follows:

$$\begin{aligned} P_{\text{rate}} &= \max\{P_1 / \eta_2, P_2\eta_2\} = \\ &\max\{| \max_{t\in[t_0,t_0+T]} \Delta P(t) \ | / \eta_2, | \min_{t\in[t_0,t_0+T]} \Delta P(t) \ | \eta_2\} \end{aligned} \tag{12}$$

In equation (12):

η_2 is the efficiency of energy storage converter C_2.

b) Energy storage capacity changes

The energy storage unit in the system should keep the energy balance inside the system. When the output power of the wind power generation system is less than the local load power, the system is in the power shortage state. The energy storage system needs to release the energy to the grid through the DC / DC converter to balance the load energy demand. The energy released by the energy storage unit during the $t \sim t+\Delta t$ time can be calculated as follows:

$$\Delta E_{\text{store}} = \Delta t[(P_{\text{load}}(t) - P_{\text{wind}}(t)) / \eta_1 - P_{\text{PV}}(t)] / (\eta_2 \eta_{\text{d}}) \quad (13)$$

In equation (13):

η_{d} is the energy storage system discharge efficiency.

On the contrary, the energy storage unit absorb energy through the DC / DC converter. The storage battery get charge. The stored energy during Δt time can be calculated as follows:

$$\Delta E_{\text{store}} = [P_{\text{PV}}(t) - (P_{\text{load}}(t) - P_{\text{wind}}(t)) / \eta_1] \eta_2 \eta_{\text{c}} \Delta t \quad (14)$$

In equation (14):

η_{c} is the storage efficiency of the energy system.

In order to monitor the charge and discharge process of the energy storage system, the state of charge (SOC) of the energy storage unit is introduced. The SOC can reflect the remaining energy of the battery. The state of the charge state at a time t can be calculated as follows:

$$S_{\text{OC}}(t) = [E_{\text{store}}(t-\Delta t) + \Delta E_{\text{store}}] / E_{\text{rate}} \quad (15)$$

In equation (15):

$E_{\text{store}}(t-\Delta t)$ is the battery energy at $(t-\Delta t)$.

ΔE_{store} is energy which energy storage unit releases or absorbs during the Δt period.

During the operation of the battery energy storage unit, the value of $S_{\text{OC}}(t)$ should fulfill requirement: $S_{\text{OC\_min}} \le S_{\text{OC}}(t) \le S_{\text{OC\_max}}$.

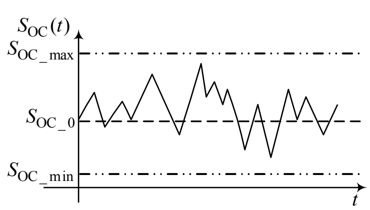

Fig. 4 SOC of energy storage system

$S_{\text{OC\_max}}$ and $S_{\text{OC\_min}}$ are the maximum and minimum permissible charge of the energy storage system, respectively. The initial value of S_{OC} is $S_{\text{OC\_0}}$. When the energy storage system works, the state of charge should be within the allowable range, as shown in Figure 4.

In the actual calculation, the value of $S_{\text{OC\_min}}$ $S_{\text{OC\_max}}$ and $S_{\text{OC\_0}}$ should be decided based on the selected energy storage system technology characteristics and application model. After the introduction of the initial value, the equation (15) can be rewritten as equation (16)

$$S_{\text{OC}}(t) = S_{\text{OC\_0}} + \sum_{t=t_0}^{t_0+n\Delta t} P_{\text{store}}(t)\Delta t / E_{\text{rate}} \quad (16)$$

During energy storage system charge and discharge process, after theoretical output ,if $S_{\text{OC}}(t+\Delta t) < S_{\text{OC\_min}}$ at the time $t+\Delta t$, then storage unit discharge capacity can be calculated as follows:

$$\Delta E_{\text{store}} = E_{\text{rate}}[S_{\text{OC}}(t) - S_{\text{OC\_min}}]\eta_{\text{d}} \quad (17)$$

After theoretical output ,if $S_{\text{OC}}(t+\Delta t) > S_{\text{OC\_max}}$ at the time $t+\Delta t$, then storage unit discharge capacity can be calculated as follows:

$$\Delta E_{\text{store}} = E_{\text{rate}}[S_{\text{OC\_max}} - S_{\text{OC}}(t)] / \eta_{\text{c}} \quad (18)$$

B. Algorithm Coding

In optimizing the capacity of t wind-PV power system, it is necessary to optimize the power and capacity of the wind , the photovoltaic power and the energy storage device. Therefore, the above four variables need to be coded in the optimization. The coding is as follows:

$$x = [x_{\text{wind}}, x_{\text{PV}}, x_{\text{Prate}}, x_{\text{Erate}}] \quad (19)$$

In equation (14):

x_{wind} is the rated power of wind power generation system;

x_{PV} is the rated power of photovoltaic power generation system.

x_{Prate} is the energy rating of the energy storage device which can be calculated by equation (12).

x_{Erate} is the rated capacity of the storage device.

VI. CASE STUDY

The simulation example uses a typical wind-PV power system, the structure is shown in Figure 1. The efficiency of the converter in the figure $\eta_1 = 97\%$, $\eta_2 = 97\%$.

A total number of hours 8760h is used, the sample interval between the load and wind/ PV power is 15min, and the maximum load is 20kW. Among them, lithium-ion battery is used as the energy storage device, the characteristics of parameters are shown in Table I.

TABLE I. TYPICAL PARAMETERS OF DIFFERENT TYPES OF BATTERIES

Parameter Type	Lithium-ion Battery
SOC Range	0.2~0.8
Charge and Discharge Efficiency η/%	90
C_{PCS}/(Yuan /kW)	2000
C_E/(Yuan /kW·h)	3000

The algorithm parameters in the simulation process are shown in Table II.

Wind power unit cost C_{wind} = 10,000 yuan / kW, photovoltaic power unit cost C_{PV} = 8000 yuan / kW, δ_{LPSP} = 0.02.

TABLE II. VALUES ASSIGNED TO THE SIMULATION PARAMETERS

Parameter Type	Value
Number of iterations	200
Population number	50
The initial value of inertia weight	0.9
The inertia weight end value	0.4
The threshold of the difference X	0.1
Mutation rate	0.05
Crossover rate	0.1

In order to verify the effectiveness of the proposed method and the economics of the wind-PV power generation system, the following four scenes are compared.

Scenario 1: Powered by a PV system alone, without wind power;

Scenario 2: Powered by wind power only, without PV;

Scenario 3: Powered by combination wind-PV power system, Conventional particle swarm optimization method is adopted.

Scenario 4: Powered by combination wind-PV power system, improved particle swarm optimization algorithm method is adopted.

The total initial investment in different scenarios and the wind power generation, PV, the energy and capacity of the energy storage device is shown in Table III.

TABLE III. OPTIMIZATION RESULTS OF DIFFERENT SCENARIOS

Parameter Type	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Power of wind/kW	-	42	22	21
Power of PV/kW	51	-	19	20
Power of energy storage/kW	33	28	21	22
Capacity of energy storage/kW·h	200	150	118	109
Total initial investment of the system/ten thousand yuan	107.4	92.6	76.8	74.1

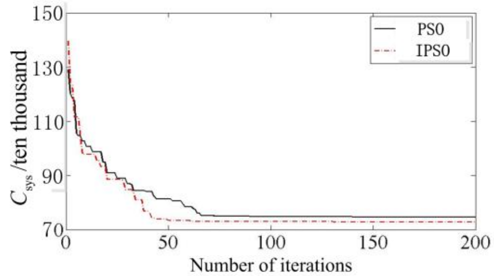

Fig. 5 Convergence curves of different algorithms

The convergence curve by different algorithms Scenario 3, 4 is shown in Fig 5.

By comparing Scenario 1, 2 with Scenario 3, 4 in Table, it can be seen that in the case where the LPSP is satisfied, by using wind-PV combined energy storage device, wind power and PV can complement each other, thus reducing the energy overflow as well as greatly reducing the total initial investment in the system.

By comparing Scenario 3, 4 in Table 3 and figure 5, it can be seen that the improved particle swarm algorithm is superior to the conventional particle swarm algorithm in convergence and search precision due to the use of adaptive inertia weight, cross mutation and other operations.

VII. CONCLUSION

In this paper, we propose a method to optimize the capacity of integrated power system of wind, photovoltaic and energy storage device with the LPSP as the constraint condition and the minimum initial investment of the system as the goal.

In the process of calculating, some shortcomings of the conventional particle swarm algorithm have been improved, and an improved particle swarm optimization algorithm is proposed. For integrated power system of wind, photovoltaic and energy storage device, under known load conditions, we conducted a simulation analysis by taking lithium ion battery as an example to seek the optimal capacity configuration between wind power, PV and storage. The simulation results show that: 1) The energy of wind power and photovoltaic power generation can be complemented in the combined power generation system, which greatly improves the utilization rate of the two and greatly reduces the total initial investment of the system. 2) The improved particle swarm algorithm proposed in this paper has a good convergence and global search capacity.

In this paper, we only consider the total initial installation cost of the system when optimizing the configuration, in the future study, the battery cycle life need to be further considered, full battery life cycle cost model should be established, which is conducive to more accurate scenery storage capacity configuration.

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