2020 19th International Symposium on Distributed Computing and Applications for Business Engineering and Science (DCABES)

Optimal Capacity Planning of Isolated Multi-energy Microgrid Considering Multi-dimensional Uncertainties

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***Abstract*—In recent years, microgrid technology has gradually been proved to be an effective method to solve the power supply problem in remote areas. The optimization goal of the planning model is to minimize the investment, operation and maintenance costs of the microgrid system, and the constraints include system power balance constraint, 'abandon wind and light' constraint, energy supply reliability constraint, etc. Then a mixed-integer nonlinear programming model is established, and the particle swarm optimization algorithm is used to find the optimal solution of this problem, after calculation, the optimal capacities of the WT, PV and battery in the microgrid are obtained. Simulation results indicate that the optimal configuration capacity obtained can minimize the total cost of the system while ensuring energy supply reliability and reducing wind and light abandonment as much as possible.**

Keywords-isolated microgrid; capacity optimal configuration; PSO

I. INTRODUCTION

For many decades, the conventional power grid has the problems of the high cost of long-distance transmission construction and serious power loss. Therefore, for typical remote areas such as islands and deserts, most of the power supply comes from diesel generators. However, the traditional diesel power generation technology is not only expensive but also pollutes the environment, which greatly limits the economic development of remote areas. Recently, with the improvement of microgrid technology, the independent microgrid system composed of wind power generation, photovoltaic power generation and energy storage equipment has successfully made up for the shortcomings of the traditional grid. At present, the microgrid system has become the key technology to solve the power supply problem in remote areas [1-2]. However, the optimization of the microgrid is a complex and systematic problem. Among them, the optimal capacity configuration of wind turbines, PV sources and energy storage devices is one of the most challenging issues in microgrid planning and investment. The capacity configuration through carefully cost-benefit analysis is fundamental to ensure the economic and stable operation of the energy system [3]. Therefore, it is of great significance to study the optimal capacity configuration method of a microgrid for microgrid construction.

The capacity optimization problem of the microgrid system is a complicated optimization problem with multiple variables. The swarm intelligence optimization algorithm has become the main method to solve this problem. In study [4], in order to prolong the lifetime of the battery, an enhanced energy management strategy was used, and a multi-objective GA algorithm was proposed to optimize the system. However, the genetic algorithm only randomly mutates, lacking the advantage of approaching the optimal solution in the PSO algorithm. For the mixed integer programming (MIP) problem, the genetic algorithm is considered to converge to the local, rather than the global optimal solution. Therefore, in order to optimize the capacity of a microgrid system consisting of various components, including wind, solar and diesel-based power generation sources as well as battery systems, a multi-objective self-adaptive differential evolution algorithm was adopted in [5]. The solution provided the theoretical analysis for supporting the capacity planning of microgrids. The authors in [6] proposed an optimization design method of island microgrid system based on a Levy-harmony algorithm and triangular aggregation model by introducing Levy flight and search preference mechanism into the standard harmony search algorithm, which enhanced the algorithm's global search capability and convergence speed. The study in [7] proposed a new multi-objective optimization algorithm to improve the coupling relationship in the renewable system, which could maximize its contribution to the peak load while minimize the intermittency and costs.

In this paper, the optimal capacity planning for an isolated microgrid consisting of different forms of distributed renewable generation sources, i.e. WT and PV and energy storage units are exploited. The main technical contributions of this work can be summarized as follows: (1) A multi-energy microgrid planning model considering system uncertainties is proposed. The objective function in this paper is to minimize the total cost of the system in an operation cycle. (2) The PSO algorithm is used to figure out the optimal capacities of the wind turbine, PV sources and battery units, and the loss of power supply probability (LPSP) is adopted to estimate the power supply reliability of the system.

The rest parts of this paper are organized as follows: Section II presents the problem formulation; Section III outlines the proposed PSO based algorithmic solution for optimal capacity planning solution. The solution is assessed through case studies in Section IV. Finally, the conclusive remarks are given in Section V.

II. PROBLEM FORMULATION

The microgrid's structure discussed in this paper is shown in Figure 1. Photovoltaic power generation and wind power generation are connected to the microgrid at the same time. To reduce the impact of environmental changes on the stability of the isolated microgrid, electric energy storage systems are connected to adjust and coordinate the energy flow of each period. Suppose that there are both translatable loads (such as electric vehicles, large-scale washing machines, etc.) and interruptible loads (such as heat loads, refrigeration and air-conditioning

2473-3636/20/$31.00 ©2020 IEEE
DOI 10.1109/DCABES50732.2020.00075

systems) in the microgrid, during operation, WT, PV generation, energy storage and various types of loads operate in harmony to maintain the power balance between supply and demand.

A. Objective

The purpose of this article is to minimize the total cost as much as possible while ensuring the reliability and stability of power supply system, and reducing the probability of wind and light abandonment:

$$f\left(x_W, x_{PV}, x_b\right) = \min C_{\cos t}^{total}$$
$$C_{\cos t}^{total} = C_{invest} + C_{Operation} \tag{1}$$

where $C_{\cos t}^{total}$, C_{invest}, $C_{Operation}$ denote the total cost, equipment investment costs, operation and maintenance costs respectively. Here, the variables in (1) are given below:

$$C_{invest} = C_W \cdot x_W + C_{PV} \cdot x_{PV} + C_b \cdot x_b \tag{2}$$

$$C_{Operation} = \sum_{T=1}^{N} \begin{pmatrix} C_{Operation,W} \cdot \left(\alpha_W\right)^T x_W \\ +C_{Operation,PV} \cdot \left(\alpha_{PV}\right)^T x_{PV} \\ +C_{Operation,b} \cdot \left(\alpha_b\right)^T x_b \end{pmatrix} \tag{3}$$

In the formula, x_W, x_{PV}, x_b denote wind power, photovoltaic, battery's configuration capacity, C_W, C_{PV}, C_b denote wind power, photovoltaic, battery's investment cost of per unit capacity, $C_{OM,W}$, $C_{OM,PV}$, $C_{OM,b}$ denote the operation and maintenance cost of wind power, photovoltaic and battery, $N=12$, $\alpha_W, \alpha_{PV}, \alpha_b$ denote monthly depreciation rate of the wind turbine, PV and battery storage unit.

B. Constraints

- Power balance constraint:

$$P_{load}^t = P_W^t + P_{PV}^t + P_b^t \tag{4}$$

Equation (1) is the power balance constraint at time t. P_{load}^t, P_W^t, P_{PV}^t, P_b^t denote the load, wind turbine, PV source and battery unit's output power at time t. If the battery system is in the state of charge, $P_b^t < 0$; if the battery system is in the state of discharge, $P_b^t > 0$.

- Capacity constraints:

Wind turbine capacity constraint:

$$N_{W,\min} \le N_W \le N_{W,\max} \tag{5}$$

Photovoltaic capacity constraint:

$$N_{PV,\min} \le N_{PV} \le N_{PV,\max} \tag{6}$$

Battery capacity constraint:

$$N_{b,\min} \le N_b \le N_{b,\max} \tag{7}$$

$N_{W,\min}$ / $N_{W,\max}$, $N_{PV,\min}$ / $N_{PV,\max}$, $N_{b,\min}$ / $N_{b,\max}$ and $N_{con,\min}$ / $N_{con,\max}$ denote the minimum and maximum capacity of the wind turbine, PV source, battery unit and Bi-directional converter respectively.

- Operational constraints:

The wind power operational constraint:

$$0 \le P_W^t \le P_{W,\max} \tag{8}$$

Photovoltaic operational constraint:

$$0 \le P_{PV}^t \le P_{PV,\max} \tag{9}$$

The bi-directional converter operational constraint is expressed in (10):

$$0 \le P_{con}^t \le P_{con,\max} \tag{10}$$

The battery operational constraints：

$$\begin{cases} SOC_{\min} \le SOC_t \le SOC_{\max} \\ -P_{b-c,\max} \le P_b^t \le P_{b-d,\max} \end{cases} \tag{11}$$

P_W^t, P_{PV}^t, P_{con}^t denote the output power of WT, PV and bi-directional converter at time t, $P_{W,\max}$, $P_{PV,\max}$, $P_{con,\max}$ denote the maximum output power of WT, PV and bi-directional converter, $SOC_{\max}$ and $SOC_{\min}$ denote the maximum and minimum state of charge of the battery, in this paper, their values are 0.8 and 0.2, SOC_t denotes the state of charge of the battery at time t, $P_{b-c,\max}$ and $P_{b-d,\max}$ denote the maximum charge and discharge power of the battery.

In the case that the planned capabilities of the WTs and PVs are insufficient, the reliability of power supply system will not be guaranteed; when the configuration capabilities of the WTs and PVs are too large or the capacity configuration of the energy storage device is too small, it will cause the problem of abandoning wind and light. Therefore, this article needs to introduce another two important constraints:

- Abandon wind and light constraint：

On each day of the planning cycle, when there is a surplus after the photovoltaic and wind power generation minus the load consumption, the battery is in the state of charge, and the spare capacity of the battery in that day should be bigger than the surplus value as much as possible.

$$(P_W^t + P_{PV}^t - P_{Load}^t) \bullet \Delta t \le N_{b,\max} \bullet (SOC_{\max} - SOC_t) \tag{12}$$

- The guaranteed efficiency constraint of power supply system：

When the photovoltaic and wind power generation is no more than the load consumption, the battery is in discharging state. At this time, the remaining energy in the battery plus the wind power and photovoltaic power generation should be bigger than the load consumption.

$$(P_W^t + P_{PV}^t) \bullet \Delta t + N_{b,\max} \bullet (SOC_t - SOC_{\min}) \ge P_{Load}^t \bullet \Delta t \tag{13}$$

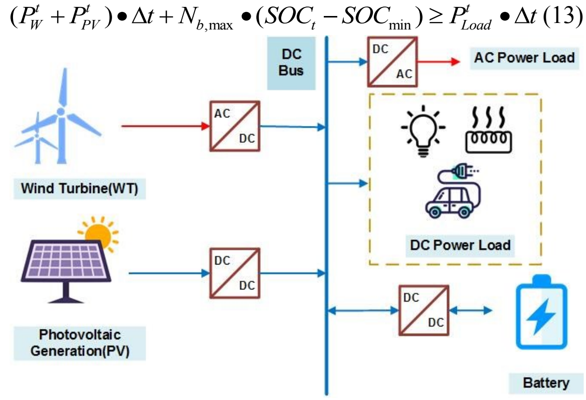

Figure 1. Proposed system configuration

III. PROPOSED ALGORITHMIC SOLUTION

In this work, the Particle Swarm Optimization (PSO) algorithm is adopted to address the optimization problem of capacity planning. The overall process of the optimization is illustrated in Fig. 2.

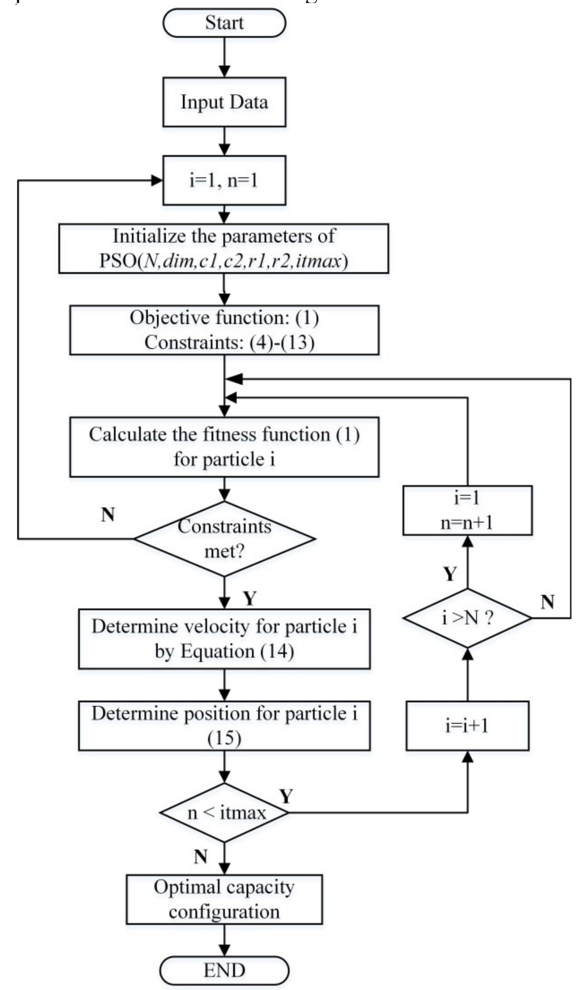

Figure 2. Overall flowchart of the capacity planning using PSO algorithm

PSO is considered as a global random search algorithm based on swarm intelligence to simulate the migration and grouping behavior of the bird swarm foraging process. The main idea behind PSO-based optimization is as follows [8]: each particle contains the information representing the position and velocity of the individual, and an adaptation value function that determines the target's fitness. During each iteration, the individual particles in the population move closer to their own optimal and group optimal directions, and finally the optimal solutions can be identified. The speed and position update formula of the particles can be expressed as follows:

$$v_i^{k+1} = \omega^k v_i^k + c_1 r_1^k (P_{best\_i}^k - x_i^k) + c_2 r_2^k (P_g^k - x_i^k) \quad (14)$$

$$x_i^{k+1} = x_i^k + v_i^{k+1} \quad (15)$$

In the formula, i represents the i^{th} particle; k is the number of algorithm iterations; c_1 and c_2 are learning factors. ω is the inertia weight coefficient; r_1 and r_2 are random numbers between [0, 1]; v is the particle update speed; x is the position of the particle; P_g is the best position in the global history; P_{best_i} is the best position in the individual history.

The right part of (14) is composed of three parts. The first part is the original velocity inertia part of the particle without interference from itself and the outside; the second part is the trend of the particle to its best position in history; the last part is the particle's trend to the best position of population history.

To avoid blind search in the iterative process, the position and velocity of the particles are generally limited to a certain interval. During the operation process of particle swarm optimization, the movement of particle swarm is influenced by the local and global optimal solutions, but finally it will converge to the global optimal solution.

IV. CASE STUDY

Considering an industrial park with PV and WT generation in a certain place in China, the park covers an area of about 210,000 m^2. The maximum electric load value is 99.04MW. The profiles of wind and PV power generation as well as the load demand through a year are adopted and normalized, as shown in Fig. 3. In this study, the parameters of various types of microgrid components are derived from study [9] and given in Table I.

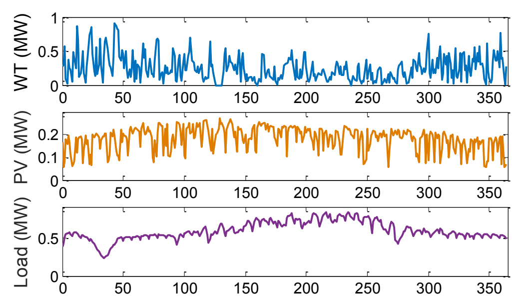

Figure 3. Normalized WT/PV/load profiles (mean)

The sampling interval of the data in this paper is one hour and the sampling period is one year, but the curve in the figure above is represented by the daily average values.

TABLE I. EXPERIMENTAL PARAMETERS OF THE MICROGRID

	$C_{invest}(\$/MW)$	$C_{Operation}(\$/MW)$	$\alpha_{equ}(\%)$
WT	12000	0.015	2%
PV	10000	0.01	1%
Battery	1000	0.0018	1%

In this paper, the optimization variables are PV, WT and battery's capacities, so the particle dimension $dim = 3$, the number of particles N is set as 40, the inertia factor ω =0.9, acceleration constant $c_1 = c_2 = 2$, the maximum iteration number is set as 100 in this study.

In this work, taking every 20 tests as a group, the statistics of the optimal solution among 20 times is considered as the output value of this group; in total of 5 groups of tests are performed, and then the average value of the 5 groups is taken as the final optimization result.

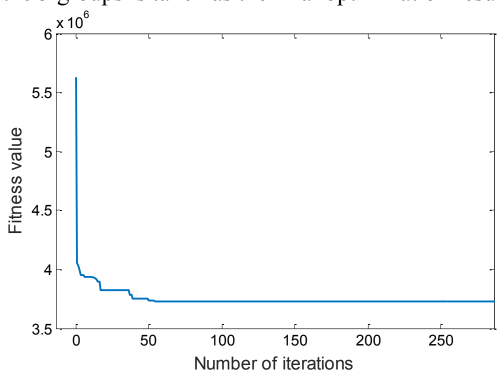

Figure 4. Convergence curve of PSO algorithm

TABLE II. CAPACITY CONFIGURATION OPTIMIZATION RESULTS

Configuration Capacity	***WT (MW)***	***PV (MW)***	***Battery (MW)***
Mean value	42.88	192.76	1285.93

TABLE III. OBJECTIVE FUNCTION VALUES

Cost	$C_{inves}(e^4\$)$	$C_{Operation}(e^4\$)$	$C_{cost}^{total}(e^4\$)$
Mean value	372.87	0.1784	373.04

In the case that the average values in Table II are adopted as the optimal configuration capacity in the microgrid planning, the constraints in the planning model are met. Under this situation: (1) The power balance of the microgrid in each day (the data in June 2015 as an example) is shown in Fig.5 Also, the loss of power supply probability (LPSP) is adopted to assess power supply reliability of the microgrid system:

$$L_{LPSP} = \frac{\sum_{t=1}^{8760}(P_{Load}^t - P_W^t - P_{PV}^t)}{\sum_{t=1}^{8760} P_{Load}^t} \approx 2.215\% \tag{14}$$

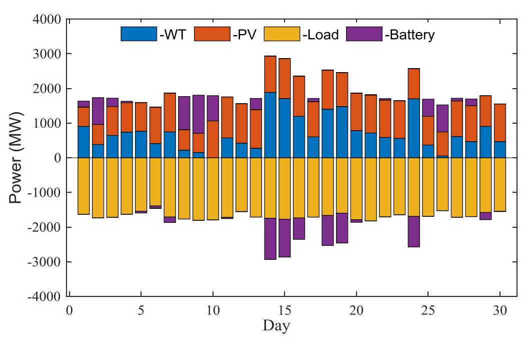

Figure 5. Power balance chart for each day in June 2015

It can be found that the numerical result is less than the maximum value of LPSP (in general 5%), therefore, it can be considered that the proposed microgrid capacity optimization model is well solved.

V. CONCLUSION AND REMARKS

This paper optimizes the capacity of an isolated microgrid, taking the minimum investment cost, operation and maintenance cost as the objective function, and the system power balance, reducing wind and light abandonment as constraints; The PSO algorithm is adopted to solve the planning model and the optimal capacity of each device is obtained; Finally, LPSP is used to evaluate the power supply reliability under this capacity configuration.

The disadvantage of this paper is that only electric load is considered, the influence of different kinds of electric load on the microgrid as well as the battery's state of charge are not specifically considered, and the microgrid's structure is relatively simple. In future work, more units can be added to the microgrid, and multi-energy system planning with DGs is also considered.

ACKNOWLEDGMENT

This study is funded by the Science and Technology Project of State Grid Zhejiang Electric Power Co., Ltd. (Research on the evaluation of the distributed renewable energy consumption based on the generation-network-demand coordination in the electricity market), and the National Natural Science Foundation of China (51777183).

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