Open Access Journal

Journal of Power Technologies 99 (4) (2019) 231–236

journal homepage:papers.itc.pw.edu.pl

Optimal Configuration of Standalone Wind–Solar–Storage Complementary Generation System Based on the GA-PSO Algorithm

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Abstract

The capacity configuration of the standalone wind–solar–storage complementary power generation system (SWS system) is affected by environmental, climate condition, load and other stochastic factors. This makes the capacity configuration of the SWS system problematic when the capacity configuration method of traditional power generation is used. An optimal configuration method of the SWS system based on the hybrid genetic algorithm and particle swarm optimization (GA-PSO) algorithm is proposed in this study to improve the stability and economy of the SWS system. The constituent elements of investment, maintenance cost and various reliability constraints of the SWS system were also discussed. The optimal configuration of the SWS system based on GA-PSO was explored to achieve the optimization objective, which was to minimize investment and maintenance costs of the SWS system while maintaining power supply reliability. The investment and maintenance costs of the SWS system under different configuration methods were calculated and analyzed on the bases of the monthly mean wind speed, solar radiation and load data of Xiaoertai Village in Zhangbei County of Hebei Province in the last 10 years. Results show that the optimal configuration method based on the GA-PSO algorithm could effectively improve the economy of the system and meet the requirements of system stability. The proposed method shows great potential for guiding the optimal configuration of the SWS system in remote areas.

Keywords: wind-solar-storage complementary, optimal configuration, hybrid genetic algorithm and particle swarm optimization (GA-PSO), objective function

1. Introduction

Energy and environmental issues have become an urgent problem with the development of the social economy. This has provided great impetus for a switch away from fossil energy to clean energy for power generation purposes. Among the many renewable energy options, wind and solar energies have been utilized on a large scale because of their widespread availability and mature technology. The standalone wind–solar–storage complementary power generation system (the SWS system) has become a means to provide electricity and solve local power shortage in remote areas where power resources are scarce [1].

Traditional energy configuration methods cannot meet the configuration requirements of the SWS system owing to the intermittent, random and fluctuating characteristics of wind and photovoltaic powers [2]. Some SWS systems have increased the configuration proportion of their energy storage capacity to overcome the instability of wind and photovoltaic power supply and ensure power supply reliability. The increased proportion of energy storage capacity also increases the cost of the SWS system. In addition, the life span of energy storage devices is limited and maintenance is difficult, thereby further increasing the cost of the SWS system. Therefore, reducing the cost of SWS system construction and maintenance through rational configuration of system capacity has become the study focus in this field.

Accordingly, researchers worldwide have studied the reliability constraints, optimization objectives and optimal configuration algorithms of the SWS system [3–5]. However, the optimal configuration of the SWS system is affected by numerous factors, such as the environment, climate and load. Current optimal configuration algorithms cannot easily meet the requirements of the SWS system due to the multi-objective, multi-variable and non-linear nature of their configuration problem. Therefore, an optimal configuration algorithm that is stable and economical should be explored urgently to maintain the reliability of the SWS system power supply.

For this reason, the the SWS system configuration was optimized using the genetic algorithm and particle swarm optimization (GA-PSO) algorithm to maintain the reliability of the power supply with minimum investment and maintenance costs. The optimal configuration methods of various SWS systems were calculated and analyzed to provide technical support for the design and implementation of the optimized SWS system.

2. State of the art

Researchers globally have conducted studies in the field of optimal configuration and have amassed a certain body of results. Abbassi et al. used a statistical method to study the capacity configuration of mixed energy storage devices in the SWS system and found that the peak power caused by the load can be effectively eliminated by reasonably allocating the super-capacitor and battery capacity of mixed energy storage devices. However, the overall capacity configuration of the SWS system was not studied [6, 7]. Gutierrez et al. studied the distribution and complementary characteristics of wind and solar resources and provided technical support for the collaborative construction of wind and solar power stations. However, the optimal configuration of wind and solar power station capacity was not discussed [8, 9]. Nguyen et al. proposed an optimal capacity allocation method for batteries and hydrogen systems to optimize the power generation cost of a system, although the results are only suitable for areas with abundant hydrogen resources [10]. Chattopadhyay et al. studied the optimal allocation of large scale grid-connected wind and photovoltaic powers, although they did not consider optimal allocation in terms of the SWS system [11, 12].

Zhu et al. studied the optimal configuration of storage battery capacity to create a continuous power supply in a standalone wind–solar–storage micro-grid system, although they did not consider the economy of this standalone system [13]. Xu et al. studied the optimal configuration of the SWS system in terms of power supply reliability, but the investment and maintenance cost of system was not considered [14]. MA et al. used particle swarm optimization (PSO) to optimize the configuration of a wind–solar pumped storage desalination system in an island-isolated network, but the study results are only applicable to areas with pumped storage power stations [15, 16].

The multi-energy independent power supply system has been the subject of various studies. Olatomiwa et al. studied the optimal configuration of this system in rural clinics from the perspective of power supply reliability, but investment and maintenance costs were excluded [17]. Ahadi et al. studied the optimal allocation of a wind-solar-diesel standalone power supply in terms of economy and stability, but the optimization performance should be further improved [18]. Haidar et al. made a comprehensive analysis of the optimal configuration of a hybrid wind-photovoltaic power generation system, but without a specific optimization strategy [19]. Iqbal et al. used economic operation and carbon emissions as optimization indicators to simulate and analyze the optimal operation of a micro-grid, but they did not consider the stability and economy of the system [20–22].

The optimal configuration of multi-energy complementary power generation systems in different application forms has been studied. However, only a few studies have analyzed the optimal configuration of the SWS system, particularly considering such comprehensive factors as construction cost, maintenance cost and system power supply reliability. Therefore, the present study proposed an optimal configuration method of the SWS system based on the GA-PSO algorithm to provide a reliable standalone power supply in remote areas. The constituent elements of the investment and maintenance costs of the SWS system and various reliability constraints of the system were studied. The optimal configuration of the SWS system was studied by using minimum investment and maintenance costs of the SWS system as optimization objectives and the GA-PSO algorithm as the optimization algorithm. The investment costs under different configuration methods were calculated and analyzed.

The next sections of this paper are organized as follows: Section 3 constructs the objective function and reliability constraints of the SWS system and proposes the optimal configuration method of the SWS system on the basis of the GA-PSO algorithm. Section 4 presents a case to verify the optimal configuration method proposed in this study, then analyzes and discusses the results. Section 5 sets out the conclusions.

3. Methodology

3.1. Objective Function

Reliability and economy are key indicators for evaluating the SWS system. Therefore, the investment and maintenance cost of the SWS system was deemed as an optimization objective.

(1) Initial investment cost of the system. The initial investment cost is as follows:

$$\begin{aligned} C_{\mathrm{ic}} = {} & \frac{T}{T_{\mathrm{W}}}\left(Q_{\mathrm{W}} \times C_{\mathrm{unit,W}}\right) + \frac{T}{T_{\mathrm{PV}}}\left(Q_{\mathrm{PV}} \times C_{\mathrm{unit,PV}}\right) \\ & + \frac{T}{T_{\mathrm{BAT}}}\left(Q_{\mathrm{BAT}} \times C_{\mathrm{unit,BAT}}\right) + \alpha\left(Q_{\mathrm{W}} \times C_{\mathrm{unit,W}}\right) \\ & + \beta\left(Q_{\mathrm{PV}} \times C_{\mathrm{unit,PV}}\right) \end{aligned} \tag{1}$$

where T is the time in which the system can be recycled; T_W, Q_W and $C_{unit,W}$ are the use time of the wind power system, system capacity, and capacity cost, respectively, of a single wind turbine; T_{PV}, Q_{PV} and $C_{unit,PV}$ are the use time of the photovoltaic system, system capacity and capacity cost, respectively, of a single photovoltaic generation system; T_{BAT}, Q_{BAT} and $C_{unit,BAT}$ are the battery life, system capacity and capacity cost of a single battery, respectively; α is the construction and installation price coefficient of the photovoltaic generation system; and β is the construction and installation price coefficient of a wind turbine.

(2) System operation and maintenance cost. The operation and maintenance cost ($C_{O\&M}$) mainly refers to the cost of maintaining equipment during operation of the SWS system. The calculation formula is as follows:

$$C_{\mathrm{O\&M}} = \sum_{i=1}^{N}\sum_{j=1}^{M} C_{i,j} TH_i \tag{2}$$

where $C_{i,j}$ is the single unit capacity of a certain type of generation equipment and TH_i is the maintenance cost per unit capacity of the i-th type equipment. This study does not consider the maintenance cost of the battery.

(3) Objective function construction. With regard to the initial investment, operation, and maintenance costs of the system, the optimization objective function is as follows:

$$LCE(¥/\mathrm{kWh}) = \frac{\left(C_{\mathrm{ic}} + C_{\mathrm{ogu}}\right) \times CRF}{\sum_{t=1}^{8760} E_{\mathrm{gen}}(t)} \tag{3}$$

where CRF is the capital recovery rate; LCE is the levelized cost of energy, i.e., all the costs of power generation system are converted into cash; and E_{gen} is the power generated by the power generation system within a unit hour.

3.2. Reliability Constraints

System reliability constraints can be described by the expected energy not supplied (EENS) and energy index reliability (EIR).

(1) Expected energy not supplied. The calculation formula of EENS in the SWS system is as follows:

$$\mathrm{EENS} = \sum_{i=1}^{N} E_i \times P_i \tag{4}$$

where P_i represents the probability of the i-th capacity case, E_i is the amount of charge that the load cannot satisfy, and N is the number of types of different capacities. EENS indicates that the electric energy generated by the power generation system is less than the electric energy required by the user. Thus, the EENS value should be considerably reduced during system design.

(2) Power supply reliability. The calculation formula of EIR is as follows:

$$\mathrm{EIR}_i = 1 - \frac{E_i}{E_{\mathrm{L},i}} = \frac{W_{\mathrm{PV},i} + W_{\mathrm{WT},i}}{E_{\mathrm{L},i}} \tag{5}$$

where $E_{L,i}$ is the total amount of electricity required by the load in the i-th month, $W_{PV,i}$ is the photovoltaic capacity in the i-th month, and $W_{WT,i}$ is the wind power capacity in the i-th month. When designing the system, the EIR value should not be under 0.9.

(3) Additional power supply rate of system

In addition, the generator set may provide power in excess of load demand. The excess power (AP) can be calculated as follows:

$$AP = \sum_{i=1}^{12} W_{\mathrm{PV},i} + \sum_{i=1}^{12} W_{\mathrm{WT},i} - \sum_{i=1}^{12} E_{\mathrm{L},i} \tag{6}$$

The system's additional power supply rate (RAP) can be calculated as follows:

$$RAP = AP/\sum_{i=1}^{12} E_{\mathrm{L},i} \tag{7}$$

A low RAP value indicates a very economical system design.

3.3. System Optimization Configuration Based on the GA-PSO Algorithm

The basic idea of the hybrid GA-PSO algorithm is to introduce the selection mechanism and crossover mechanism of a genetic algorithm (GA) into the PSO. After each PSO iteration, the particles to be crossed are selected with a certain probability and placed in the hybridization pool. The particles in the hybridization pool are randomly combined to produce offspring particles that will be used to replace the parent particles. Thus, the generated descendant particles inherit the advantages of parent particles and the search ability of particles is strengthened at the same time. The GA-PSO algorithm overcomes the problem of the traditional PSO algorithm–which readily falls into the local optimum–and improves the global searching ability of the PSO algorithm.

Therefore, the GA-PSO algorithm was used in this study to realize the optimal configuration of the SWS system. The specific steps are as follows.

Step 1: Input historical weather data

Input the meteorological data observed by the weather station for nearly 10 years, then calculate the monthly mean wind speed and the monthly average solar radiation amount accordingly. In the absence of wind power and photovoltaic power, the battery capacity is determined to be the sum of a three-day load demand.

Step 2: Determine algorithm parameters

Randomly generate a population containing M particles. Initialize the particles, i.e., initialize the initial value of PV and wind power capacity to PPV0 and PWT0, respectively. Attribute a a random speed to each particle and set the step size of wind power and photovoltaic capacity variation. The number of iterations is set as N.

Step 3: Update particle speed and position

According to Eqs. (8) and (9), update the velocity and position of particles. Thereafter, calculate the values of photovoltaic and wind power capacity as follows:

$$v_i^{k+1} = \omega v_i^k + c_1 r_1 \left(x_{\mathrm{pbest},i}^k - x_i^k\right) + c_2 r_2 \left(x_{\mathrm{gbest}}^k - x_i^k\right) \tag{8}$$

$$x_i^{k+1} = x_i^k + v_i^{k+1} \tag{9}$$

where v_i^k is the k-th iteration velocity of the particle $i(i = 1, 2, \ldots, M)$, x_i^k is the k-th iteration position of the particle i, $x_{pbest,i}^k$ is the optimal position of particle i at the k-th iteration, x_{gbest}^k is the optimal position of the group at the k-th iteration, ω is the inertia weight, c_1 and c_2 are the learning factors, and r_1 and r_2 are the random numbers between [0–1].

Step 4: Particle crossing and mutation calculation

After updating the position of particles, select some particles as the population for cross-genetic calculation. Assume that there are parents X_1 and X_2 as follows:

$$\begin{cases} X_1 = (x_{1,1}, \cdots, x_{1,i}, \cdots, x_{1,n_1}) \\ X_2 = (x_{2,1}, \cdots, x_{2,i}, \cdots, x_{2,n_1}) \end{cases} \tag{10}$$

According to Eq. (11), the two parents are crossed as follows:

$$\begin{cases} \overline{X_1} = \lambda X_2 + (1-\lambda) X_1 \\ \overline{X_2} = \lambda X_1 + (1-\lambda) X_2 \end{cases} \tag{11}$$

where λ is a random number in the interval [0–1].

A particle $X(x_{m,1}, \ldots, x_{m,i}, \ldots, x_{m,n})$ is selected with a certain probability, and a component $x_{m,i}$ of the particle is subjected to mutation calculation to obtain a new individual $X'(x_{m,1}, \ldots, x'_{m,i}, \ldots, x_{m,n})$.

Step 5: Calculate the particle fitness value and constraints

Calculate the investment and maintenance costs of all particles according to the objective function. Determine the fitness value of particles according to the particle investment and maintenance costs and sort the particles according to the fitness value. Determine whether the particles satisfy the constraint. If the constraint is satisfied and the number of particle iterations has been completed, then the optimal PV and wind power installed capacity and the corresponding costs are output. If the constraint is not met, or the maximum number of iterations is not reached, then proceed to Step 3.

The overall flow chart of GA-PSO is shown in Fig. 1.

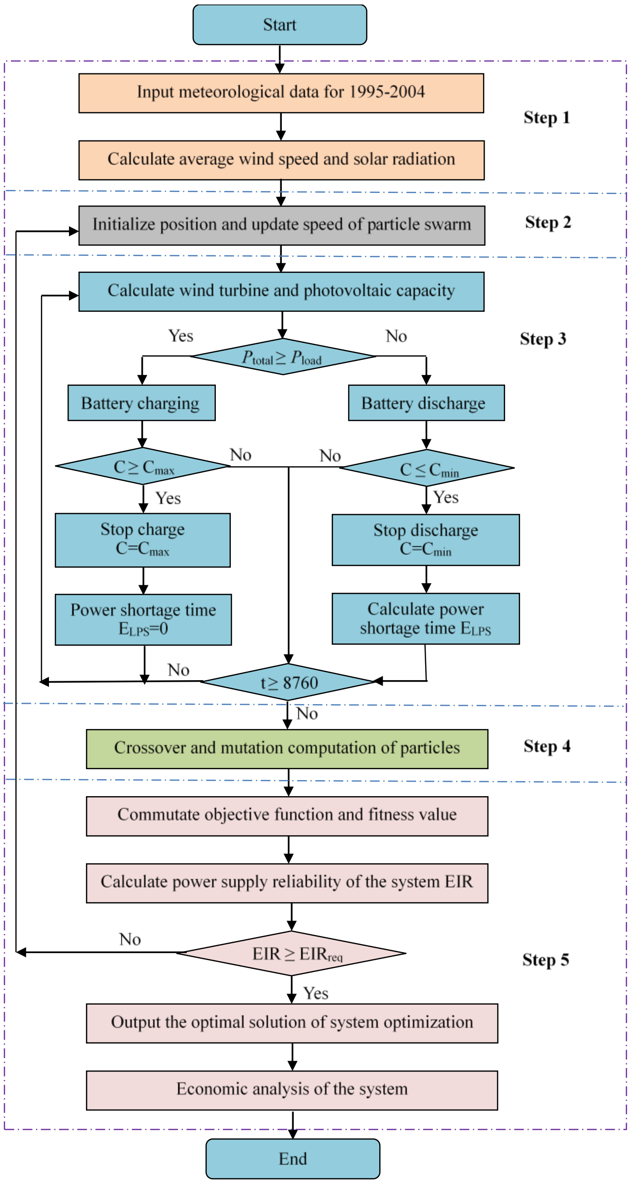

Figure 1: Flowchart of the algorithm

4. Result analysis and discussion

Xiaoertai Village in Zhangbei County of Hebei Province was chosen as the calculation object where the correctness of the proposed algorithm will be verified. This region has extensive wind and solar energy resources and is distant from urban areas. In addition, Xiaoertai Village only has a few, relatively stable load types and lacks large-scale power enterprises. Therefore, this region is well-suited to construction of the SWS system. Fig. 2 shows the monthly average load for the past 10 years in the region.

Fig. 3 shows the monthly average solar peak radiation hours and the monthly average wind speeds of meteorological data for the past 10 years in Xiaoertai Village.

Three configuration methods were calculated and analyzed to ensure that the power supply reliability is above 0.9.

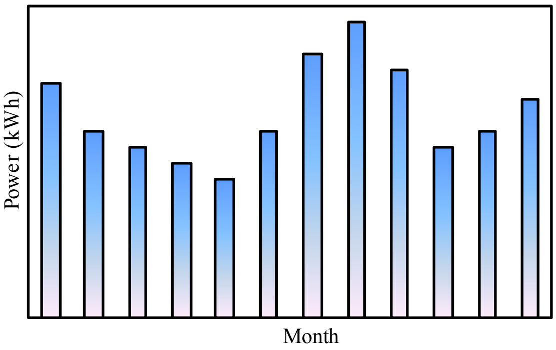

Figure 2: Monthly average load power

(1) Only considering wind power, use the wind resource

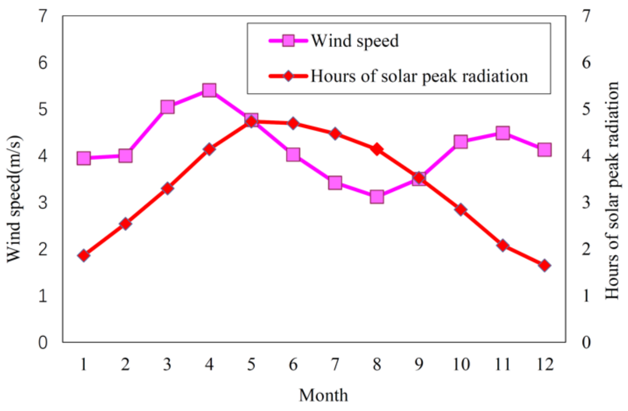

Figure 3: Monthly average solar peak radiation hours and monthly average wind speeds

data of the year to determine the annual power generation of wind power system and configure wind power capacity.

(2) Only considering photovoltaic power, use the solar radiation energy of the year to determine the annual power generation of photovoltaic array and configure photovoltaic power capacity.

(3) Simultaneously considering wind power and photovoltaic, an optimization model of the SWS system was established based on the annual load curve of the system. The wind and photovoltaic capacities were optimized by the GA-PSO algorithm to determine the optimal capacity configuration.

In the three configurations, battery capacity is directly determined according to the sum of three days of load. In this study, the largest three-day load, which was 25 kW, was selected as the battery capacity.

Table 4 shows the investment and maintenance costs for the three configurations, where PV, WT, and PV+WT are the investment and maintenance cost of photovoltaic power, wind power, and combined wind and photovoltaic powers, respectively.

Table 1: Investment costs in three configurations

Cost and capacity	PV+WT	PV	WT
Total cost (Ten thousand RMB)	27.55	40.8	113.85
Photovoltaic capacity (kW)	26	51	0
Wind power capacity (kW)	15	0	253

The power outputs of the wind power and photovoltaic power after optimization are shown in Fig. 4.

The monthly average net load shown in Fig. 5 was obtained by subtracting the monthly average load from the sum of the monthly average wind power output and photovoltaic power output. Fig. 5 shows that the optimized wind and photovoltaic power can meet load demand except in January, August, and December. For those three months, the sum of wind and photovoltaic outputs is less than the load because the monthly average solar peak radiation hours and monthly average wind speeds are too low.

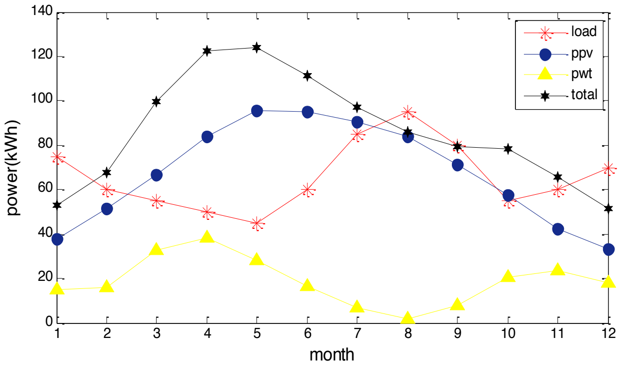

Figure 4: Power output and load levels after optimization

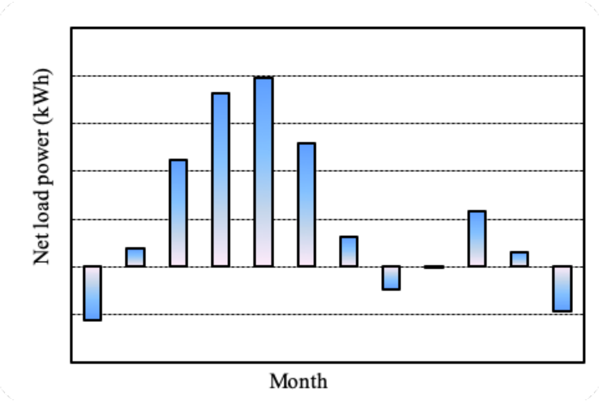

Figure 5: Monthly average value of net load

Table 2 shows the calculation results of power supply reliability and additional power supply rate for the optimized SWS system in the years 2012-2015. The annual reliability rate of the power supply is approximately 0.9, which satisfies system requirements. In addition, the system's additional power supply rate is between 50% and 80%, thereby ensuring safe and stable operation of the system.

Table 3 shows the optimal configuration results of the PSO algorithm and GA-PSO algorithm.

Table 3 shows that the configuration capacity of wind turbines is the same under the two optimization algorithms, but the optimized photovoltaic capacity based on the GA-PSO algorithm is lower than that of the PSO algorithm. Therefore, the overall investment cost of the GA-PSO algorithm is less than that of the PSO algorithm.

Table 2: Power supply reliability and additional power generation 2012-2015

Year	EIR	RAP
2012	92.8%	78.96%
2013	89.68%	60.72%
2014	87.52%	47.04%
2015	91.84%	60.7%

Table 3: Optimization configuration results of PSO and GA-PSO

Algorithm	PV Capacity (kW)	Wind Capacity (kW)	Total cost (Ten thousand RMB)
PSO	30	15	30.75
GA-PSO	26	15	27.55

5. Conclusion

This study addresses the issue of optimal configuration of the SWS system. The optimization objective was to minimize investment and maintenance costs of the system. The expected energy not supplied and energy reliability index were considered as system reliability constraints. The GA-PSO algorithm was then used to calculate and analyze the optimal configuration of the SWS system. The conclusions are as follows.

(1) The GA-PSO algorithm can effectively complete the optimal configuration calculation of the SWS system, and the optimization results of the GA-PSO algorithm are better than those of the PSO algorithm.

(2) The optimized configuration of the SWS system is more economical and meets the requirements of power supply reliability.

This study proposed an optimal configuration method fully considering the economy and security of system of the SWS system based on the GA-PSO algorithm. The correctness of the proposed method was verified by an actual example. The study results play a positive role in promoting use of the SWS system.

Acknowledgements

This study was funded by the Key Projects of Science and Technology in Henan Province (152102210117) and the Science and Technology Project of the National Power Grid Corporation Headquarters (SGHADK00PJJS1500060). The authors also wish to thank those people who provided extensive assistance, but whose names are not listed in the paper.

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