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Design of An Intelligent Monitoring and Control System for Photovoltaic Microgrids

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Abstract. This article focuses on the problems of imperfect models and slow convergence speed of optimization algorithms in the use of photovoltaic microgrids. Firstly, accurate mathematical models are established based on the composition of photovoltaic microgrids, namely photovoltaic power generation systems and energy storage systems. Then, an improved cat swarm algorithm is used to solve the model, ultimately achieving an increase in solving speed during the process while avoiding the algorithm from falling into local optima. Finally, an intelligent monitoring system for photovoltaic microgrids was designed based on the algorithm process of the article, visualizing the main parameters.

Keywords: photovoltaic microgrid, photovoltaic model, energy storage model, intelligence algorithms

1 Introduction

In remote areas and remote inland islands and other special locations, the use of the State Grid power system can result in high construction costs and technical difficulties. The conventional solution is to use diesel for power generation, but there are problems such as high fuel transportation costs, high price fluctuations, and serious environmental pollution. With the development of wind power and photovoltaic technology, building an independent microgrid with wind and solar renewable energy as the core according to local conditions is an important means to solve the power supply problem in special locations.

However, with the promotion of microgrid systems, there are many types of distributed power sources in independent microgrids and there are significant differences in the output characteristics of each power generation unit, which makes the problem of optimizing the configuration of microgrid capacity apparent and presents a high degree of nonlinearity, complexity, and uncertainty. This article focuses on the research of photovoltaic microgrid systems, summarizes the current problems in photovoltaic microgrid systems, and does a lot of work in this article.

The current photovoltaic microgrid system has the following problems:

1) The objective model established for the photovoltaic microgrid system is not comprehensive enough, resulting in deviations between the optimization results and actual operation.

2) For the optimization of the model, the use of constraint functions is not sufficient, and most of the optimization algorithms used are typical sparrow algorithm, ant colony algorithm, etc. Without improving the algorithm, the convergence speed of the algorithm is slow, and the solution results deviate from the optimal value.

Therefore, in response to the above issues, the work done in this article is as follows:

1) Firstly, the composition and structure of the photovoltaic microgrid were analyzed, and an accurate mathematical model was established based on the actual usage status of each structure. The model can reflect the operational status of the system and lay the foundation for subsequent optimization;

2) Analyzed and compared the advantages and disadvantages of existing optimization algorithms, selected the idea of cat swarm algorithm to optimize the model in this article, and conducted targeted research on the com-

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mon problems of slow convergence speed and easy falling into local optima in the optimization process.

In order to provide a detailed description of the work done in this article, the structure of this article is composed of the following parts. Chapter 2 mainly introduces some existing research results and related research directions, providing some reference for the main research content of this article. Chapter 3 mainly describes the process of establishing a photovoltaic microgrid model and analyzes the operation status of the power grid. Chapter 4 mainly focuses on model optimization, The main description is the optimization of the model to obtain the optimal solution for microgrid energy monitoring. As the core method of monitoring system design, Chapter 5 introduces the design and operation results of the detection system, and preliminarily completes the functional requirements. Chapter 6 is the conclusion, summarizing the work of this article, and explaining the shortcomings of the work and future prospects.

2 Related Work

Sharma Deepesh studied the matching problem of the motor rotor in the photovoltaic power generation process. In order to better improve the performance of the photovoltaic power generation system, a fuzzy controller with adaptive membership function and a deep learning control strategy were proposed [1]. Majji Ravi Kumar designed a finite control set model predictive controller for factors such as solar irradiance, feasibility of public power grids, and price fluctuations, which can achieve energy usage switching in various modules of the photovoltaic microgrid and improve energy control efficiency [2]. Chao Zhao established an independent microgrid model for wind, light, storage, and diesel, with the goal of minimizing annual system costs as the objective of optimizing the capacity configuration of the independent microgrid. Then, an improved grey wolf optimization algorithm was used to optimize the model, and finally, simulation was conducted to verify the efficiency of the optimization method [3]. Yu Li proposed a hierarchical control strategy for stable DC bus and constant load power operation of microgrid energy storage devices in island mode, and optimized the energy monitoring method. Simulation experiments have proven the effectiveness of this method [4]. Ning Zhang established an island operation mode in the wind, light, and energy storage microgrid to analyze and construct a capacity optimization configuration model for wind, light, and energy storage. The model takes the load shortage rate as the constraint condition for the reliability of the microgrid power supply, and takes the minimum operating cost of the microgrid as the objective function. Finally, the cat swarm algorithm was used for optimization, which has reference value [5]. Yu Zhang, the main research object is a hybrid photovoltaic energy storage system composed of supercapacitors and batteries. He constructed a photovoltaic DC microgrid system model, and then optimized the model using an improved bird swarm algorithm. The optimization results were verified using real annual load output data measured in a residential area in Guilin, proving the feasibility of the method [6]. Yajing Bai has designed a microgrid capacity management system based on power collectors. The system consists of an energy local area network and an energy sub network energy management system, and can adopt expert control strategies, including normal operation, fault handling, and island operation modes. The model design scheme has reference significance [7].

3 Modeling of Photovoltaic Power Generation Systems

The photovoltaic microgrid system described in this article consists of a photovoltaic power generation system and a hybrid energy storage system, therefore, each system is modeled.

3.1 Mathematical Model of Photovoltaic Cells

When the light intensity is at a stable value, the current generated by the photoelectric effect will not be changed, which can be equivalent to an ideal current source with a current value of I_{lx} . For the convenience of description, an equivalent model of photovoltaic cells is established [8], as shown in Fig. 1.

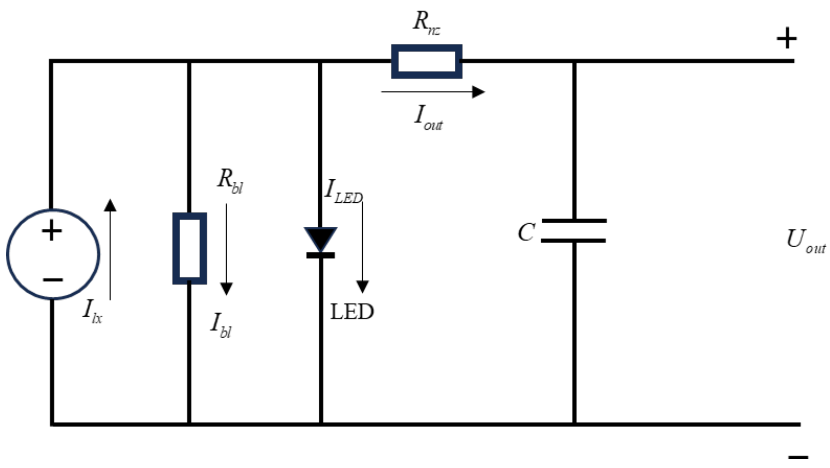

Fig. 1. Equivalent model of photovoltaic cells

In the figure, *LED* is the equivalent diode of the photovoltaic cell, *C* is the equivalent capacitance of the photovoltaic cell, R_{nz} is the internal resistance of the photovoltaic cell, and R_{bh} is the parallel resistance of the circuit, which provides protection for the entire circuit. Generally, the protection resistance value is relatively high, and $R_{sh} \geq 1k\Omega$.

According to Kirchhoff's law, the current of the entire circuit can be expressed as:

$$I_{out} = I_{lx} - I_{LED} - I_{bl}. \tag{1}$$

The relationship between current and voltage in section $P-N$ satisfies the following formula:

$$I_{LED} = I_{bh}\left(e^{q(U_{out}+IR_{nz})/(AKT)} - 1\right). \tag{2}$$

$$I_{bl} = \frac{U_{out} + IR_{nz}}{R_{bl}}. \tag{3}$$

Therefore, by organizing the above formulas, the following current expression can be obtained:

$$I_{out} = I_{lx} - I_{bh}\left(e^{q(U_{out}+IR_{nz})/(AKT)} - 1\right) - \frac{U_{out} + IR_{nz}}{R_{bl}}. \tag{4}$$

In the above formula, I_{out} represents the output current of the photovoltaic cell, U_{out} represents the output voltage of the photovoltaic cell, I_{bh} represents the reverse saturation current of the diode, q represents the amount of electronic charge, K is the Boltzmann constant, A is the ideal factor of $P-N$, and T is the absolute temperature. In practical application, the above model needs to be simplified, and the value of R_{bl} is relatively small. After simplification, the following results are obtained:

$$I_{out} = I_{lx}\left[1 - B\left(e^{U_{out}/CU_{kl}} - 1\right)\right]. \tag{5}$$

In the formula, U_{kl} is the open circuit voltage, and at the maximum power point, $U_{out} = U_{\max}$, $I_{out} = I_{\max}$, therefore, at the maximum power point of the photovoltaic cell, the following formula can be obtained by sorting:

$$I_{\max} = I_{lx}\left[1 - B\left(e^{U_{\max}/CU_{kl}} - 1\right)\right]. \tag{6}$$

Under normal temperature conditions, environmental factors have a significant impact on batteries, so the corrected values for environmental factors are as follows:

$$\Delta t = t - t_{ref}. \tag{7}$$

$$I_{lx}^{'} = I_{lx}\left(1 + a\Delta t\right). \tag{8}$$

$$U_{kl} = U_{kl}\left(1 - c\Delta t\right)\ln\left(e + b\Delta t\right). \tag{9}$$

$$I_{\max}^{'} = I_{\max}\left(1 + a\Delta t\right). \tag{10}$$

$$U_{\max}^{'} = U_{m}\left(1 - c\Delta t\right)\ln\left(e + b\Delta s\right). \tag{11}$$

$t = 25$˚C and $s = 1000W/m^2$ represent the temperature and light intensity under standard conditions, respectively. $a = 0.0025$/ ˚C. $b = 0.5$ and $c = 0.0029$/ ˚C are both correction coefficients.

4 Intelligent Detection and Control Algorithm for Power Grid Energy

The photovoltaic system should meet the constraints of providing sufficient power load and ensure that the average annual system cost of the microgrid is the lowest. The photovoltaic microgrid in this article consists of three parts: annual initial investment cost, operation and maintenance cost, and environmental pollution control cost [9]. Therefore, the objective function is expressed as:

$$\min C_{GF} = \min\left(C_T + C_{YW} + C_H\right). \tag{12}$$

In the formula, C_T represents the annual initial investment cost of the photovoltaic microgrid, including the annual acquisition cost and installation cost of the photovoltaic microgrid, C_{YW} represents the annual operation and maintenance cost of the photovoltaic microgrid, and C_H represents the environmental governance cost of the photovoltaic microgrid.

The average annual initial investment cost of the system is:

$$C_T = \sum_{j=1}^{n}\left(M_j \alpha_j P_j\right)\frac{\eta\left(1+\eta\right)^t}{\left(1+\eta\right)^t - 1}. \tag{13}$$

The average annual operating and maintenance cost of the system is:

$$C_{YW} = \sum_{j=1}^{n} c_{YW,j} M_j P_j. \tag{14}$$

Annual average environmental governance cost of the system:

$$C_H = \sum_{k=1}^{N} v_k\left(F_k + F_k^{'}\right). \tag{15}$$

4.1 Constraint Condition

In the monitoring process of the power grid, it is necessary to consider constraints such as the balance of system energy supply and demand, as well as limitations on the output power of each power source. Therefore, the generation capacity constraints of photovoltaic microgrids are:

$$P_{GF}\left(t\right)+P_{D}\left(t\right)\geq P_{F}\left(t\right). \tag{16}$$

Battery *SOC* constraint, in order to ensure that the battery has good working characteristics, the state of charge of the battery should be within the allowable range:

$$SOC_{\min}\leq SOC\left(t\right)\leq SOC_{\max}. \tag{17}$$

All parameters involved in the above formula are shown in Table 1:

Table 1. Parameter list

Parameter symbols	Parameter
M_j	Number of *j* -type power sources
α_j	Operation and maintenance coefficient of type *j* power supply
P_j	Rated power of type *j* power supply
η	Depreciation rate
l	Life
$c_{YW,j}$	Operation and maintenance coefficient of type *j* power supply
N	Types of pollutants
v_k	Emission of Type *k* pollutant
S_k	The Environmental Value of Type *k* Pollutant
$S_k^{'}$	Pollution Penalty for Type *k* Pollutant
$P_{GF}(t)$	Output power of photovoltaic modules
$P_D(t)$	Output power of battery pack
$P_F(t)$	Power required by load
$SOC_{\min}$	Minimum value of battery state of charge
$SOC_{\max}$	Maximum value of battery state of charge

4.2 Intelligent Algorithm Solving Process

The energy monitoring of photovoltaic microgrids is actually an automatic adjustment of the optimal capacity configuration of the microgrid. This article uses an improved intelligent algorithm to solve the power grid control problem. The algorithm uses the cat swarm algorithm and is represented in pseudocode form [10]. The process is as follows:

```
Start:
Set up: Initialize the position of the cat population within the constraint range, with the number of
    cat populations A and the number of iterations B;
Set up: Initialize the position of the cat group and calculate the function value corresponding to the
    cat group;
Int MR;
    The proportion of the number of cats in the total number of cat groups un der tracking mode is
    randomly divided into tracking mode and search mode based on the grouping rate
Search for (SMP) (SPC) (SRD) (CDC)
Track
If (Reached Iterations)
    then output optimization results
else if
    Repeat the above process
End
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When searching for mode, set parameters: including memory pool (*SMP*), self position judgment (*SPC*), dimension change domain (*SRD*) , and dimension change number (*CDC*). Copy the current position of the j cat group: when *SPC* is true, $j = SMP - 1$; Otherwise, $j = SMP$. Update the copied cat group according to *CDC* and *SDR*. Copy the function values of all samples from *SMP*, find the copy sample corresponding to the optimal function value, and replace the current position of the cat to update the cat's position in search mode.

When in tracking mode, update the position of the cat group by changing the speed of the cat.

5 System Design and Simulation Result Analysis

5.1 System Structure Design

The monitoring system is divided into three parts: organizational level, coordination level, and execution level. The system uses a microcontroller as the control center to collect and issue data and instructions for each device, and communicates with the upper computer system through Ethernet. The real-time collected device data is uploaded to the data collection terminal for data calculation. The system structure is shown in Fig. 2.

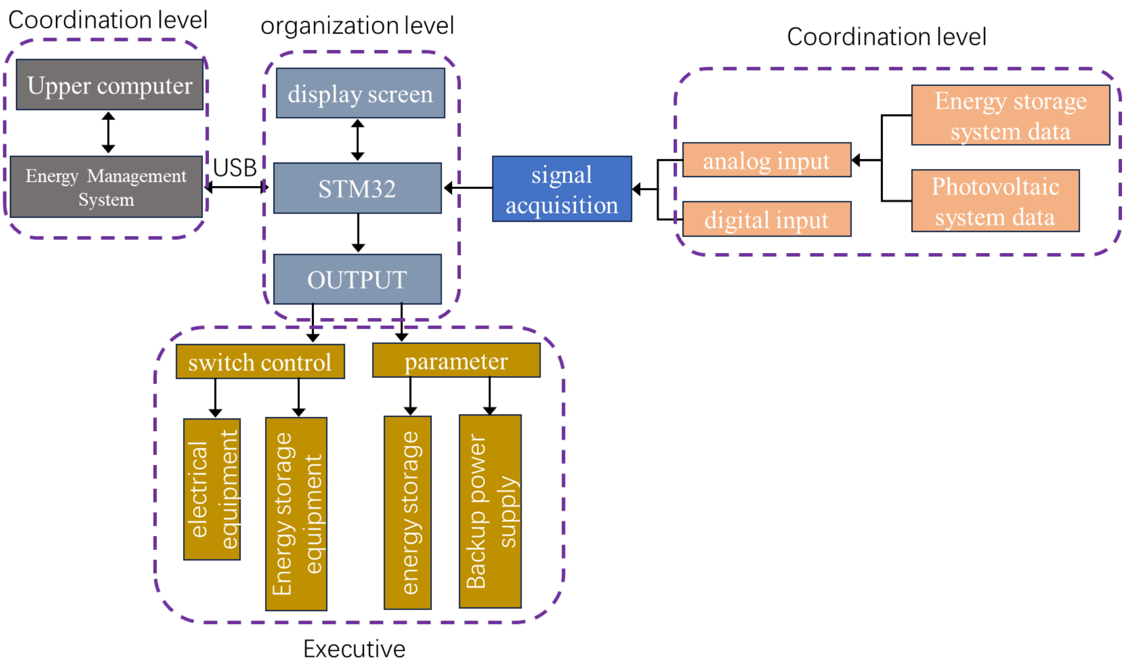

Fig. 2. System logic diagram

Structurally, the entire system is divided into four major parts: energy management system, STM32 controller, signal acquisition, and signal output. The photovoltaic data is connected to the microcontroller through a USB data cable, and the photovoltaic system data is transmitted to the control core through the microcontroller pins. The connection method between STM32 and the upper computer also uses a USB data cable to upload real-time collected device data to the WINCC data acquisition terminal.

5.2 Software Design

The software mainly consists of five parts: system overview, device data, energy management, report statistics, and alarm information.

A system overview includes system structure, photovoltaic system, and energy storage system, displaying the structure diagram of the entire system and real-time equipment operation data;

1) Equipment data mainly includes real-time operation data display interfaces for photovoltaic system equipment, energy storage system equipment, and backup power supply equipment;

2) Energy management mainly includes the prediction curve of photovoltaic power generation, real-time power curve of photovoltaic power generation, and real-time power curve of photovoltaic/energy storage/load/backup power supply;

3) The report statistics mainly include data records of photovoltaic system output power, energy storage system discharge power, energy storage system charging power, load power, grid acquired power, and backup power output power;

4) The alarm mainly includes various types of alarm information that occur during system operation.

The system interface is shown in Fig. 3.

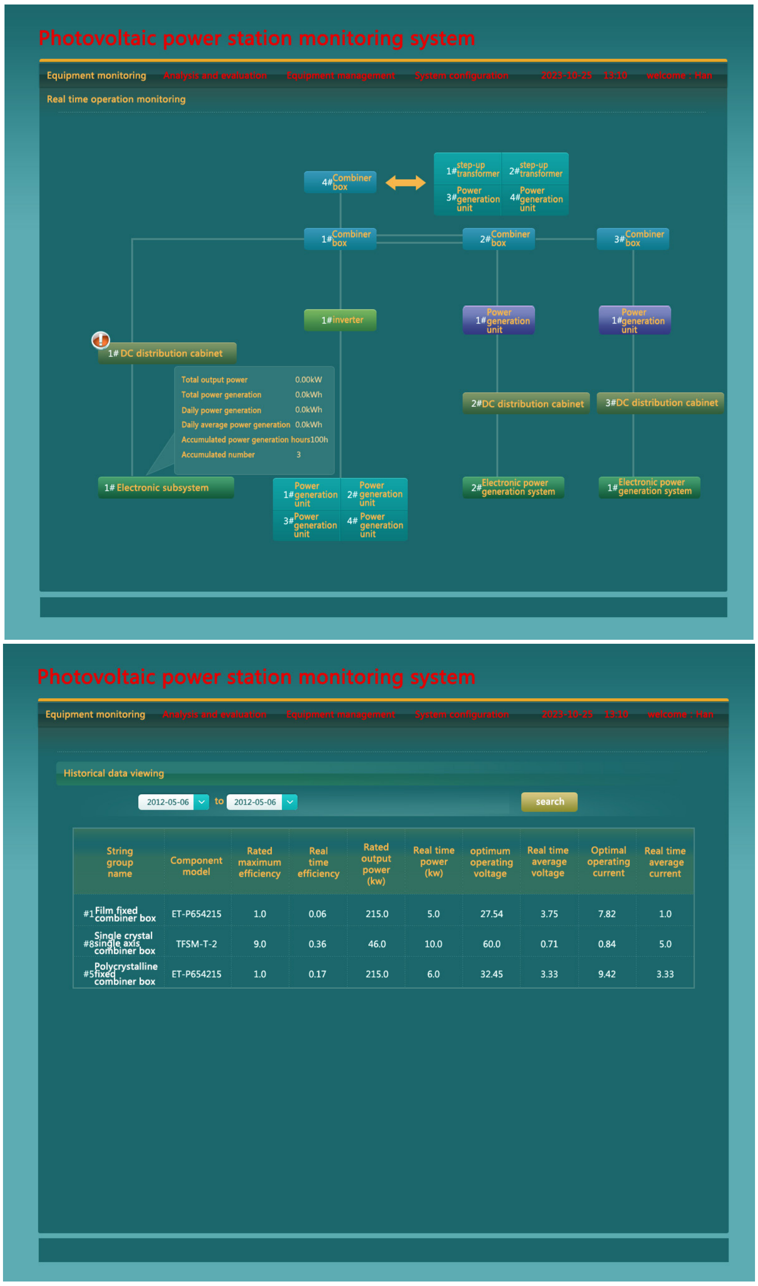

Fig. 3. System interface

5.3 Intelligent Monitoring Experiment

To verify the effectiveness and stability of the small-scale grid connected photovoltaic optimization control system designed and developed in this chapter, the microgrid was operated in grid connected mode by setting parameters.

According to the predicted photovoltaic output power, the energy storage system is charged during low valley electricity prices from 0:00 to 4:00 in preparation for discharging to the load during peak electricity prices during the day. From 11:30 to 12:30, it can be seen that the actual photovoltaic output power is greater than the load demand power. At this moment, the energy storage system stores the excess energy. Over time, the energy storage system discharges to the load during the three peak electricity price periods of 13:00 to 15:00, 15:30 to 17:00, and 19:00 to 21:40, respectively, resulting in a downward adjustment of the blue purchasing power curve and a reduction in user electricity costs. From the above experimental verification, it can be seen that the optimized control system can effectively control the energy storage system in the grid connected state based on the predicted photovoltaic power and the formulated optimization control strategy, and reasonably control the energy storage system for charging and discharging according to the changes in each output power, thereby achieving the optimal comprehensive cost-effectiveness of the microgrid.

6 Conclusion

This article addresses the issues of incomplete models in the use of photovoltaic microgrids, and establishes an accurate mathematical model based on the composition of the photovoltaic microgrid. The process of establishing the mathematical model fully considers the actual operation of the photovoltaic microgrid. In the model optimization environment, cat swarm algorithm is used to optimize the model. The convergence speed and local optimization issues inherent in the cat swarm algorithm have also been corrected, ultimately achieving the design of the system. This article also has the following shortcomings. It will be the main research direction in the future:

1) Not fully considering the impact of shadows on photovoltaic power generation systems when photovoltaic systems are arranged in different environments;

2) Although the cat swarm algorithm has made simple modifications, it cannot guarantee the same applicability when calculating more complex models;

3) The visualization and human-machine interaction of the system need to be improved.

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